HYDROFLUORIC ACID (HF) ALKYLATION: PROCESS, MATERIALS, AND SUPPLY CHAIN

An Industry White Paper

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Executive Summary

Hydrofluoric acid (HF) alkylation is one of the most demanding processes in refining. While it provides high-octane alkylate essential for clean gasoline production, it also presents unique challenges in safety, metallurgy, and supply chain management. Few areas of a refinery combine such severe corrosion mechanisms, such strict regulatory oversight, and such high consequences of failure.

From a materials perspective, HF service is unforgiving. Corrosion behavior is governed not only by alloy type but also by **trace residual elements** in carbon steels, water contamination, and velocity effects. To mitigate these risks, industry practice has converged on **Low Residual Element (HF-N) carbon steels** defined through ASTM supplementary requirements (A106 S9, A333 S2, A960 S78, A961 S62) and complemented by API RP 751 and NACE guidance. Where dry HF service can be reliably contained in HF-N steels, **wet HF or high-velocity environments demand nickel alloys** such as Alloy 400 (Monel) or Inconel 600. Materials not designed for this duty — particularly stainless steels, copper alloys, or uncontrolled commodity steels — can fail rapidly and catastrophically.

The challenge is compounded by global steelmaking trends. With the shift from integrated BF–BOF routes to scrap-based EAF production, controlling residual elements has become increasingly difficult. HF-qualified material is therefore scarce, subject to **long lead times, high minimum order quantities, and frequent quality lapses** when procurement is not rigorously specified and audited.

This is precisely where **BUHLMANN Group** differentiates itself. As one of the few distributors with deep expertise in HF metallurgy, we enforce ASTM HF-N clauses across all product forms, demand melt-level and product-level chemistry verification and perform 100% PMI on critical components. By aggregating refinery demand globally, we justify HF-N heats at partner mills and maintain strategic inventory, enabling us to deliver project-sized quantities of compliant pipe, fittings, flanges, valves, and plates when they are needed most.

In a market where mistakes in metallurgy can have life-threatening consequences, **BUHLMANN** stands apart by combining **technical authority, rigorous QA/QC, and supply chain discipline**. Our mission is simple: to ensure that every component delivered for HF service is not only available, but also **safe, compliant, and traceable** — protecting both people and plants.

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1. Introduction

Alkylation has been a cornerstone process in refining for more than eight decades, producing the high-octane blending components required to meet modern fuel standards. **Hydrofluoric acid (HF) alkylation was first commercialized in the late 1930s**, following joint development by UOP and Sun Oil. The technology rapidly expanded during **World War II**, when alkylate became essential for aviation gasoline, and in the post-war decades it established itself as one of the most efficient and compact alkylation processes available. Today, HF alkylation units still account for a significant share of global alkylation capacity, underscoring both their efficiency and long operational history.

Three main alkylation technologies are in use today:

- **Sulfuric acid alkylation** – widely deployed, avoids HF-specific hazards, but requires large volumes of acid, extensive logistics, and costly spent acid handling.
- **Hydrofluoric acid (HF) alkylation** – compact and efficient, first commercialized in the 1930s and still widely used, but with unique safety, environmental, and metallurgical challenges.
- **Ionic liquid alkylation (e.g., ISOALKY™)** – the newest alternative, aiming to deliver HF-like efficiency with improved safety and environmental performance, though adoption remains limited.

This white paper focuses specifically on **HF alkylation**, where the intersection of **safety, metallurgy, and supply chain discipline** makes material selection one of the most critical success factors for refiners.

Hydrofluoric acid is highly toxic and corrosive, demanding stringent controls on unit design, operations, and emergency preparedness. Industry standards such as **API RP 751** and licensor guidelines set the framework for safe operation, while past incidents have highlighted the consequences of lapses in design or material control.

From a materials perspective, HF service is unforgiving. Equipment reliability depends not only on alloy type but also on **trace residual elements** in carbon steels, the presence of water, and velocity effects. **Low Residual Element (HF-N) carbon steels**, defined through ASTM supplementary requirements (A106 S9, A333 S2, A960 S78, A961 S62, A516 S54), are widely used in dry HF service. In contrast, **wet HF environments or high-velocity areas** require nickel alloys such as Alloy 400 (Monel) or Inconel 600 to ensure long-term integrity. An incorrect materials selection, or failure to enforce chemistry restrictions, can result in rapid and catastrophic failure.

Compounding these technical challenges are persistent **supply chain constraints**. HF-qualified steels are produced by only a limited number of mills, often with long lead times and high minimum order quantities. The global shift from blast furnace to scrap-based electric arc furnace (EAF) production has further increased the difficulty of controlling residual elements, making rigorous QA/QC and traceability essential.

This is where **BUHLMANN Group** brings unique value. With decades of experience in HF alkylation metallurgy and supply, we enforce HF-N supplementary requirements across all product forms, demand both ladle- and product-level chemical verification and perform 100% PMI on high-risk components. By aggregating global refinery demand, we secure HF-N heats with partner mills and maintain strategic inventory for critical dimensions. This combination of **technical expertise, QA/QC discipline, and supply chain capability** ensures that every component delivered for HF service is not only available when needed, but also **safe, compliant, and fully traceable**.

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2. HF Alkylation Process Overview

2.1 Process Sections

HF alkylation combines light olefins (propylene, butylene) with isobutane to produce **alkylate**, a premium blending component with high octane and low vapor pressure. The process operates in three main sections:

1. **Reaction Section** – Olefins (propylene, butylene) are mixed with isobutane and contacted with circulating HF catalyst in the reactor system. The reaction produces alkylate and acid-soluble oils (ASOs). HF is continuously recycled, while ASOs are purged to maintain catalyst activity.
2. **Fractionation Section** – The reactor effluent passes through a settler where the HF-rich acid phase is separated and returned to the reactor. The hydrocarbon phase is then fractionated in a

series of columns (typically a deisobutanizer and debutanizer) to recover isobutane for recycle and to separate the final alkylate product.

3. **Treating Section** – The treating system removes contaminants, stabilizes acid strength, and ensures proper HF quality for continued operation. This includes regeneration steps to manage ASOs and maintain catalyst performance.

This compact three-section design explains why HF alkylation units are efficient, high-yield, and comparatively smaller in footprint than alternative technologies.

2.2 Process Licensors

HF alkylation technology was first developed in the late 1930s by **UOP and Sun Oil**, with the first commercial units starting up just before World War II. Since then, several licensors have offered HF alkylation processes, each with variations in reactor design, acid circulation, and safety systems.

The main licensors today include:

1. **UOP (Universal Oil Products)** – one of the original licensors, with extensive global operating experience.
2. **Stratco (now part of DuPont/Albemarle)** – historically active in both HF and sulfuric acid alkylation, with proprietary reactor designs.
3. **ConocoPhillips** – developed its own HF process and continues to support a fleet of licensed units.

Although licensors differ in design details, all follow the same fundamental process steps and operate within the framework of **API Recommended Practice 751**, which defines industry standards for HF unit safety, operation, and integrity.

2.3 Advantages and Disadvantages

HF alkylation has remained in widespread use for more than eight decades because of its clear advantages:

- **High catalyst activity** and efficient conversion of olefins to alkylate.
- **Compact unit design**, requiring less plot space compared to sulfuric acid alkylation.
- **Excellent alkylate quality**, producing a blending component with high octane, low vapor pressure, and no sulfur or aromatics — ideal for meeting clean fuel standards.

- **Catalyst recycling**, as HF is continuously recovered and reused, reducing net catalyst consumption.

These benefits, however, are balanced by significant disadvantages:

- **Severe safety hazards** – HF is highly toxic, corrosive, and volatile. Even small releases can create ground-hugging vapor clouds with catastrophic potential for workers and nearby communities.
- **Metallurgical demands** – Materials of construction must be carefully controlled, with Low Residual Element (HF-N) steels for dry service and nickel alloys in wet or high-velocity areas. Improper material selection can lead to rapid failure.
- **Regulatory and community scrutiny** – HF alkylation units face increasing pressure from regulators, local authorities, and the public due to safety concerns.
- **Supply chain challenges** – HF-qualified materials are limited to a small number of mills, with long lead times, high minimum order quantities, and frequent QA/QC risks if not carefully specified.

2.4 Hazards & Safety Considerations

Hydrofluoric acid presents hazards unlike any other refining process. HF is **toxic, corrosive, and highly volatile**. Even a small release can generate dense, ground-hugging vapor clouds that travel long distances and pose serious risks to workers and surrounding communities. Direct contact causes deep tissue burns, and inhalation can be fatal at very low concentrations.

Because of these risks, HF alkylation is subject to strict industry standards and regulatory oversight. **API Recommended Practice 751** sets the benchmark for unit design, materials of construction, operation, maintenance, and emergency preparedness. Licensor guidelines further reinforce these requirements, incorporating decades of operating experience and lessons learned from past incidents.

Key safety measures include:

- **Water mitigation systems**, designed to absorb and neutralize HF vapor in the event of a release.
- **Inventory minimization**, limiting the volume of HF in areas most vulnerable to leaks.
- **Specialized metallurgy**, with HF-N steels and nickel alloys to ensure equipment integrity under corrosive service.
- **Operator training and emergency drills**, given the unique medical protocols required for HF exposure.

Ultimately, the safe operation of an HF alkylation unit is inseparable from the **integrity of its materials of construction and supply chain discipline**. A single non-compliant component — whether a pipe spool, fitting, or valve — can undermine both unit reliability and community safety. This linkage between safety, metallurgy, and procurement rigor provides the foundation for the next section of this paper.

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3. Metallurgy & Material Requirements

3.1 Corrosion Mechanisms in HF Service

HF alkylation is uniquely demanding from a materials standpoint. Corrosion is influenced not only by the alloy selected, but also by **residual element chemistry, water contamination, temperature, and velocity**. Key mechanisms include:

- **Residual element sensitivity** – Elevated levels of Ni, Cu, Cr, Mo, V, or Nb in carbon steels accelerate corrosion and embrittlement.
- **Water content** – The presence of water increases HF aggressiveness, particularly in recycle systems and low-flow areas.
- **Velocity effects** – High fluid velocities, especially in elbows, pumps, and valve seats, can strip protective films and trigger localized attack.
- **Temperature impact** – Although HF alkylation operates at moderate temperatures, localized hot spots can exacerbate corrosion rates.

3.2 HF-N Supplementary Requirements

To control residual element effects, the industry relies on **ASTM supplementary requirements**, which define “Low Residual Element” or HF-N grades:

- **ASTM A106 S9** (for seamless carbon steel pipe)
- **ASTM A333 S2** (for low-temperature seamless carbon steel pipe)
- **ASTM A960 S78** (for butt-weld fittings)
- **ASTM A961 S62** (for forged flanges and fittings)
- **ASTM A516 S54** (for plates)

These clauses limit **Cu + Ni to ≤ 0.15%** (with further restrictions on Cr, Mo, V, and Nb), providing steels with improved resistance to HF corrosion. Compliance must be enforced at the purchase order level, as standard commodity grades often exceed these limits.

3.3 Suitable and Unsuitable Materials

- **Suitable materials for HF service include:**
  - **HF-N carbon steels** (for dry HF service at moderate velocities).
  - **Alloy 400 (Monel)** and **Inconel 600**, required for wet HF environments, high-velocity services, and sensitive components such as valve trims and pump internals.
- **Unsuitable materials include:**
  - **Austenitic stainless steels** – rapidly attacked in HF service.
  - **Copper and copper alloys –** highly susceptible to corrosion.
  - **Uncontrolled commodity carbon steels –** residual levels above HF-N limits make them unsafe for service.

3.4 QA/QC and Inspection Practices

Specifying HF-N metallurgy is only the first step; compliance must be **verified and maintained** throughout the supply chain. Best practices include:

- **Dual chemistry analysis** (ladle and product level) to confirm compliance with HF-N limits.
- **100% PMI (Positive Material Identification)** on fittings, flanges, and valves to prevent substitution errors.
- **Traceability audits**, ensuring that heats and batches remain segregated through fabrication and delivery.
- **Regular inspection programs** in operating units, focusing on high-risk areas such as nozzles, elbows, exchangers, and valve seats.

3.5 Common Misconceptions

Despite decades of industry experience, some misconceptions persist:

- **"All carbon steels are acceptable for HF"** – false. Only HF-N compliant steels (with restricted residuals) are suitable.
- **"API RP 751 defines chemical limits"** – false. API RP 751 provides guidance, but enforceable limits come from ASTM supplementary requirements.
- **"Stainless steels offer better resistance"** – false. In HF service, stainless steels corrode rapidly and must not be used.

3.6 Summary of HF-N Requirements

Table 1 – HF-N Supplementary Requirements for Carbon Steels in HF Alkylation

Product Form	ASTM Base Standard	HF-N Supplementary Requirement	Residual Element Limits
Seamless Pipe	ASTM A106 Gr. B	S9	Cu + Ni ≤ 0.15% (with Cr, Mo, V, Nb controlled)
Low-Temperature Pipe	ASTM A333 Gr. 6	S2	Cu + Ni ≤ 0.15% (with Cr, Mo, V, Nb controlled)
Butt-Weld Fittings	ASTM A234 WPB	ASTM A960 S78	Cu + Ni ≤ 0.15% (with Cr, Mo, V, Nb controlled)
Forged Flanges/Fittings	ASTM A105 / A350 LF2	ASTM A961 S62	Cu + Ni ≤ 0.15% (with Cr, Mo, V, Nb controlled)
Plates (Pressure Vessels)	ASTM A516 Gr. 60 / 70	S54	Cu + Ni ≤ 0.15% (with Cr, Mo, V, Nb controlled)

HF alkylation metallurgy leaves no room for error. A pipe, fitting, flange, or plate that does not comply with HF-N requirements represents not just a quality issue, but a **serious process safety risk**. For this reason, **BUHLMANN Group enforces ASTM supplementary requirements (S9, S2, S78, S62, S54) across all product forms**, ensuring residual elements remain within safe limits. Every heat is verified by both ladle and product analyses, and high-risk components undergo 100% PMI before shipment.

By combining **global supply chain reach, strategic inventory, and rigorous QA/QC discipline**, BUHLMANN guarantees that every component delivered for HF service is not only available, but also **safe, compliant, and fully traceable** — providing refiners with confidence where it matters most.

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4. Materials by Service

Material selection in HF alkylation is defined not only by general metallurgy principles, but also by **licensor piping specifications**. UOP, one of the leading licensors, has established standard HF piping classes (HF-1, HF-2, HF-20, HF-40, HF-50, etc.), which dictate materials of construction depending on service environment. These classes form the industry benchmark and are referenced by refiners worldwide.

4.1 HF Piping Classes and Service Definitions

HF Class	Typical Service	Primary Material Requirement
HF-1	Hot or wet HF acid	Alloy 400 (Monel)
HF-2	Cold HF acid, rich acid, acid-contaminated hydrocarbon	Alloy 400 or HF-N carbon steel, depending on velocity
HF-20	HF-free hydrocarbons with trace acid potential	HF-N carbon steel (ASTM A106 S9 / A333 S2)
HF-40	Utility and non-acid hydrocarbon service	Standard carbon steels (non-HF)
HF-50	Water systems	Carbon steel with internal coatings or Alloy 400, depending on exposure

Source: UOP Piping Specs for HF Alkylation Units (2017)

These classifications provide a practical framework: **critical acid service demands Alloy 400**, while **dry or non-acid services can be handled with HF-N carbon steels**, provided residual elements are controlled.

4.2 Application by Equipment

- **Reactors and Contactors** – Typically HF-N carbon steel (A516 S54, A106 S9). Internals exposed to turbulence (baffles, nozzles) are often upgraded to Alloy 400.
- **Settlers** – Constructed from HF-N carbon steel plates (A516 S54). Nozzles and circulation points often require Alloy 400.
- **Fractionators** – HF-N carbon steel for towers and trays; Alloy 400 or Inconel 600 in overhead condensers and exchangers exposed to wet HF.
- **Heat Exchangers** – HF-N carbon steel shells; Alloy 400 or Inconel 600 tube bundles in HF-contact services.
- **Piping** – Governed by HF class: HF-1 (hot/wet HF → Alloy 400), HF-2 (cold HF or contaminated hydrocarbons → Alloy 400 or HF-N CS), HF-20 (trace HF → HF-N CS).
- **Valves** – HF-N carbon steel bodies; Alloy 400 trims/seats. Stainless steels are strictly prohibited.
- **Pumps and Compressors** – Alloy 400 wetted parts for casings, impellers, and shafts.
- **Storage and Transfer** – HF-N carbon steel tanks and piping; Alloy 400 for valves and high-velocity nozzles.

4.3 Summary of Materials by Service

Equipment	Primary Material	Critical Alloy Applications
Reactors / Contactors	HF-N carbon steel (A516 S54, A106 S9)	Alloy 400 for nozzles, internals
Settlers / Circulation	HF-N carbon steel (A516 S54, A333 S2)	Alloy 400 for nozzles, high-velocity points
Fractionators / Overheads	HF-N carbon steel	Alloy 400 / Inconel 600 in overheads
Heat Exchangers / Coolers	HF-N carbon steel	Alloy 400 / Inconel 600 for tube bundles
Piping (HF-1 / HF-2 / HF-20)	Alloy 400 or HF-N carbon steel	Based on UOP HF service class
Valves	HF-N carbon steel bodies	Alloy 400 trims/seats; no stainless steels
Pumps / Compressors	Alloy 400 wetted parts	N/A
Storage / Transfer Systems	HF-N carbon steel	Alloy 400 in valves and nozzles

By aligning material specifications directly with **UOP HF piping classes** and **ASTM HF-N requirements**, refiners ensure compliance with licensor expectations while protecting against corrosion and failure. **BUHLMANN Group enforces these requirements across all product forms and services**, combining metallurgical expertise, QA/QC verification, and global supply chain capabilities.

This ensures that whether the need is for **Monel in critical HF-1 services or HF-N carbon steels for HF-20 applications**, every component is delivered **compliant, traceable, and ready for safe operation**.

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5. Steelmaking & Residual Element Control

The key differentiator for steels in HF alkylation service is not strength or toughness, but **residual element chemistry**. Trace amounts of nickel, copper, chromium, molybdenum, vanadium, and niobium can dramatically accelerate corrosion in HF service, particularly where water or velocity effects are present.

To mitigate this risk, ASTM has established **supplementary requirements** that define Low Residual Element, or HF-N grades:

- ASTM A106 S9 (seamless pipe)
- ASTM A333 S2 (low-temperature pipe)
- ASTM A960 S78 (butt-weld fittings)

- ASTM A961 S62 (forged flanges/fittings)
- ASTM A516 S54 (pressure vessel plate)

These clauses limit **Cu + Ni to ≤ 0.15%**, while also controlling Cr, Mo, V, and Nb. Compliance with these limits is mandatory for all carbon steel components in HF service.

5.1 Steelmaking Methods and Residuals

Historically, most HF-N steels were produced in **Blast Oxygen Furnaces (BOF)**, which rely on virgin iron ore and allow residuals to be tightly controlled. However, the global steel industry has shifted toward **Electric Arc Furnace (EAF)** production, which uses recycled scrap as feedstock. While more sustainable, EAF introduces higher and more variable levels of Ni, Cu, and other residuals, making HF-N compliance increasingly difficult.

This evolution in steelmaking has created **supply chain bottlenecks**:

- Mills can only produce HF-N grades in **dedicated campaign heats** with carefully selected scrap/charge mix.
- Such campaigns require **large minimum order quantities (MOQs)** and significant lead times.
- Without aggregation of demand, many refiners struggle to secure compliant materials on their own.

Table 2. Comparison of BF–BOF vs EAF Steelmaking

Feature	**BF–BOF**	**EAF**
Feedstock	Ore + coke	Scrap + DRI/HBI
Energy	Coal (coke)	Electricity
Scale	Large (>3 Mt/y)	Flexible (0.5–2 Mt/y)
Residuals	Low	High risk
CO_2 emissions	2.0–2.2 t/t	0.4–0.6 t/t
Decarbonization	Difficult	Easier (renewables)

5.2 Risks of Non-Compliance

Misapplication of commodity carbon steels in HF service remains one of the most serious risks. Even small deviations above the HF-N residual limits can result in accelerated corrosion, leaks, and catastrophic failure. While API RP 751 provides guidance on HF safety and metallurgy, **the enforceable limits are found only in ASTM supplementary requirements**. Paper certifications are not sufficient — **dual chemistry analysis** and **100% PMI** are essential to confirm compliance.

BUHLMANN Group mitigates these risks through global aggregation, strategic partnerships, and rigorous QA/QC. By combining demand across multiple refiners, we secure dedicated HF-N production campaigns from qualified mills. Every heat is tested at both ladle and product levels to confirm chemistry, and high-risk items are subjected to 100% PMI. This ensures that every pipe, plate, fitting, and flange delivered for HF service is not only available but also **safe, compliant, and traceable**.

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6. Supply Chain Challenges

Ensuring consistent availability of Low Residual Element (HF-N) materials has become one of the most difficult aspects of HF alkylation asset management. Historically, refiners could rely on major mills whose steelmaking practices naturally delivered pipe, fittings, and flanges that met supplementary Low RE specifications. Today, structural changes in the steel industry — particularly the global shift from **blast furnace/basic oxygen furnace (BF–BOF) production to scrap-based electric arc furnace (EAF)** — have disrupted this balance.

Residual element control can no longer be assumed. Compliance with ASTM supplementary requirements (A106 S9, A333 S2, A960 S78, A961 S62, A516 S54) must now be actively specified, secured at the melt stage, and verified through QA/QC. The following subsections review the specific challenges across major product categories.

6.1 Seamless Pipe

Seamless pipe has long been the backbone of HF alkylation metallurgy. Historically, sourcing compliant Low Residual Element (HF-N) pipe was straightforward, but industry shifts in steelmaking have made availability one of the most complex challenges today.

Steelmaking Evolution

In the past, most seamless pipe from North America, Europe, and Brazil was produced by **blast furnace/basic oxygen furnace (BF–BOF)** routes. Ore-based production naturally yielded low levels of Cu, Ni, and Cr, so pipe often met **ASTM A106 S9 and A333 S2** residual limits without refiners even specifying them.

Over the last decade, however, many BF–BOF mills have exited or reduced seamless capacity. Remaining producers are increasingly **electric arc furnace (EAF)-based**, relying on scrap feedstock. Scrap introduces elevated Cu, Ni, and Cr — precisely the residuals restricted in HF service. As a result, **reviewing MTRs or doing PMI after production is no longer sufficient**; chemistry control must be secured **at the melt stage** through binding purchase specifications.

Minimum Order Quantities and Economics

EAF mills can produce HF-N heats, but only with **large minimum order quantities (MOQs)**. Typical campaigns require **100–400 tons per grade**, plus 10–20 tons per diameter and schedule. For example, ordering 40 feet of 2” Schedule 160 pipe could mean committing to several thousand feet — with a total order value approaching **USD 500,000**.

For distributors, this creates a dilemma:

- Stocking Low RE pipe ties up capital and warehouse space for years.
- Outsourcing production on a project-by-project basis results in long lead times and price premiums.

This structural mismatch is one of the main reasons Low RE pipe commands such a steep premium.

Traceability and Production Practices

Modern mills optimize by cutting multiple pipe sizes from a single billet diameter. While efficient, this makes **after-the-fact PMI inadequate** — since different sizes from the same billet may vary in residual chemistry. True compliance can only be guaranteed when pipe is **melted and ordered specifically to HF-N clauses** (A106 S9, A333 S2), with dual chemistry analysis (ladle + product).

Current Availability

Despite these challenges, compliant seamless pipe is still available from select global mills, particularly in **Europe and Asia.** But refiners must **plan early, budget for premiums, and enforce strict QA/QC** to secure HF-N supply.

6.2 Low RE Butt-Weld Fittings

Butt-weld fittings are widely regarded as the **weakest link in the HF-N supply chain**. Unlike seamless pipe, which is produced in large heats with controlled chemistry, fittings are manufactured in small, fragmented batches across many diameters and wall thicknesses. This makes **chemistry consistency and traceability inherently difficult**.

Traceability Gaps

Most forging shops purchase **commodity billets** certified only to broad ASTM ranges (e.g., A234 WPB), not the tighter limits of **ASTM A960 S78**. Unless buyers explicitly specify supplemental clauses and require **product-level analysis**, there is no obligation for forges to certify residual element content on the finished item. As a result, fittings often slip through with elevated Cu, Ni, or Cr — undetectable until PMI uncovers the problem, often late in the procurement process.

Evolving Standards and Owner Requirements

Owner companies have raised the bar over the last decade. Many refiners now impose **cumulative Cu + Ni + Cr limits**, stricter than ASTM, or mandate **normalization heat treatments** to improve metallurgical stability. These requirements significantly reduce the number of fittings that qualify. Large diameters (≥16”) and heavy-wall schedules (SCH 120+) are particularly difficult, with often only one or two viable suppliers worldwide.

Regional Supply Trends

- **Korea and Japan** – Limited but consistent production of normalized fittings, mainly in ≤12” sizes.
- **India and Middle East** – High volume, but residual element control is inconsistent; PMI failures are frequent.
- **Europe** – Boutique mills supply high-quality fittings, but at premium cost and long lead times.

Risk Profile

Because each size and wall schedule may come from a different billet heat or forging batch, the **probability of non-compliance in an order is high**. Even with PMI screening, procurement often becomes a process of “selection by elimination,” generating scrap, delays, and budget overruns.

For this reason, **butt-weld fittings remain the highest-risk category in HF metallurgy** and require the most rigorous sourcing discipline.

6.3 Low RE Flanges

Compared to fittings, **flanges are generally more manageable** to source in compliant HF-N grades. The economics of forging flanges work in their favor: the majority of 2–24” flanges can be produced from a relatively small number of billet sizes. This consolidation improves heat traceability and reduces the variability that plagues butt-weld fittings.

Steelmaking Impact

When billets are produced from **BF–BOF routes**, residual levels are naturally low, and compliance with HF service metallurgy is relatively straightforward. Historically, European and North American forges consistently delivered normalized A105 or LF2 flanges that easily met Cu+Ni+Cr cumulative limits ≤0.15%.

Today, however, more billets come from **EAF scrap-based production**, where Cu and Ni contamination is higher and more variable. This makes **supplemental clauses (A961 S62)**, dual chemistry testing (ladle + product), and normalization heat treatment essential. PMI alone cannot guarantee compliance.

Regional Supply Trends

- **Europe (Italy, Spain):** Specialty forges continue to supply high-quality, normalized HF flanges, though volumes are limited.
- **North America:** Some distributors maintain stock of normalized A105 flanges tested to HF limits, often certified for toughness down to –20 °F.
- **Asia (China, India):** Dominate volume supply, but traceability is inconsistent; without HF-specific ordering, imported A105 flanges are frequently considered high risk.

Risk Profile

Flanges present **lower risk than fittings**, since fewer heats are required to cover the dimensional range. However, refiners who fail to specify HF-N clauses and normalization expose themselves to the same risks of elevated residuals and rapid corrosion.

6.4 Low RE Forged Fittings

Forged fittings — such as socket weld couplings, unions, and small-diameter tees — occupy a **medium-risk position** in the HF-N supply chain. Unlike butt-weld fittings, they can sometimes be consolidated into larger production campaigns, but in practice demand is fragmented across thousands of SKUs, making compliance inconsistent.

Production Characteristics

When purchased in large consolidated orders, forged fittings can be produced with good traceability. A few qualified forges in **Korea and Italy** can cover a full ½–2” range using only a handful of heats, minimizing variability and PMI burden.

However, most forged fittings are ordered in **small, job-specific lots**, scattered across olets, couplings, crosses, and reducers. These fragmented orders are often fulfilled by small forges or machine shops using **commodity EAF billets**, with limited traceability back to the melt.

Lead Times and Variability

Lead times vary widely:

- Commodity couplings may be available in **weeks**,
- While specialty olets or non-standard configurations can take **months**.

Because of this fragmented landscape, refiners must treat forged fittings with caution, particularly when sourcing from regions where billet traceability is weaker.

Regional Supply Trends

- **Korea/Europe:** Reputable for consistent billet sourcing and normalized products, especially for bulk ranges.
- **India/Asia:** Strong volume supply but significant variability in chemistry; PMI essential.
- **North America:** Limited forging capacity, but some distributors hold long-term inventory tested to HF-N requirements.

Risk Profile

Forged fittings do not represent the same systemic risk as butt-weld fittings, but they remain a **medium-risk category**. Procurement strategies that rely on **spot buys** instead of consolidated campaigns will face the highest exposure to non-compliant chemistry.

6.5 Low RE Valves

Valves represent one of the most complex and high-risk categories in the HF supply chain. They combine the challenges of forged billet sourcing with the added risks of casting quality, and compliance is particularly difficult in larger sizes and higher pressure classes.

Forged Valves

Forged carbon steel valves (e.g., ASTM A105N, A350 LF2) share the same billet sourcing challenges as forged fittings.

- For **small sizes (≤1")**, billets can be shared across multiple products, allowing efficient production and reasonable traceability.
- For **larger flanged valves (≥1½")**, billet diameters often exceed 200 mm. Only a handful of mills worldwide can supply HF-N compliant billets at this size, and MOQs are impractically large relative to the weight of a typical valve order. This mismatch leads to **long lead times and high premiums** for larger forged valves.

Cast Valves

Cast valves introduce additional metallurgical risks. Inclusions, porosity, and shrinkage — common casting defects — become severe liabilities in HF service, where even small flaws can initiate corrosion.

- Refiners and licensors now mandate **stringent non-destructive examination (NDE)**, including radiography (RT), ultrasonic testing (UT), and stricter porosity acceptance criteria.

- Many owner companies restrict cast valve usage altogether for critical HF lines, instead specifying forged alternatives or Alloy 400 solutions despite higher cost.

Industry Innovations

The valve supply chain has responded with several initiatives to improve HF suitability:

- **Welded-bonnet forged valves** reduce reliance on cast designs.
- **Forged Monel valves** are now available up to 4”, offering superior resistance in critical HF services.
- Industry groups (e.g., **MSS task forces**) are actively developing updated quality standards for HF valves.

Regional Supply Trends

- **Europe (Italy, Germany):** Strong reputation for high-quality forged and cast valve production, though capacity is limited and costs are high.
- **China:** High-volume supplier, but traceability and defect rates remain a major concern for HF service.
- **North America:** Specialty valve shops are emerging, focusing on niche HF designs but generally with long lead times and premiums.

Risk Profile

Valves remain among the **highest-risk categories** in HF alkylation metallurgy.

- **Small forged valves** are increasingly manageable due to product innovations.
- **Large forged or cast valves** remain scarce, with planning horizons of **12–18 months** often required to secure compliant supply.

6.6 Summary & Risk Matrix

Category	Availability	Cost Impact	Risk Level	Key Notes
Seamless Pipe	Still available, but increasingly limited to select mills	Very High (large melt MOQs, premiums)	Medium	Must secure melt-level HF-N compliance early; 9–12 month lead times typical
Butt-Weld Fittings	Very limited, especially large diameters and heavy wall	Highest	High	Weakest link in the supply chain; PMI failures frequent; few global sources for ≥16”
Flanges	Moderate; fewer billet sizes improve traceability	Moderate	Low–Medium	Easier to manage, but EAF billets require dual analysis + A961 S62
Forged Fittings	Moderate in bulk ranges; fragmented in specials	Variable	Medium	Traceability weak for job orders; consolidation improves compliance
Valves	Scarce in larger forged/cast sizes	Very High	High	12–18-month planning horizon; strict QA/QC essential; forged Monel an emerging solution

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6.7 Recommendations

Given the increasing complexity of securing HF-N steels for alkylation service, refiners must treat metallurgy sourcing as a **strategic discipline rather than a transactional purchase**. The following measures are recommended to reduce risk and ensure compliance:

1. Engage Early with Mills and Distributors

- Secure melt commitments **well in advance of planned turnarounds** (often 12–24 months).
- Build long-term partnerships with qualified mills and distributors experienced in HF-N metallurgy.

2. Specify Supplemental Requirements in Contracts

- Always order to **ASTM HF-N clauses**: A106 S9, A333 S2, A960 S78, A961 S62, A516 S54.

- Require **dual chemistry testing (ladle + product)** in addition to PMI.
- Where appropriate, define cumulative residual limits (Cu + Ni + Cr) beyond ASTM minimums.

3. Implement Rigorous QA/QC and PMI

- Require **100% PMI** on fittings, flanges, and forged items.
- Utilize third-party inspectors at the **melt stage** for critical orders.
- Maintain full traceability of heat numbers, MTRs, and PMI results.

4. Prioritize High-Risk Categories

- Allocate additional budget and lead time for **butt-weld fittings and valves**.
- Where possible, **standardize valve and fitting sizes** to reduce SKU fragmentation.

5. Plan for Premium Costs and Inventory Strategy

- Accept that HF-N materials carry significant **premiums**.
- Consider **pooling orders across corporate sites** or units to meet MOQs.
- Distributors should weigh the trade-off between **holding inventory vs. outsourcing production**.

6. Adopt Multi-Sourcing Strategies

- Avoid reliance on a single supplier for critical categories.
- Maintain at least **two qualified sources** for pipe, fittings, flanges, and valves.

7. Monitor Industry and Standards Development

- Track mill capacity shifts, particularly the global **BOF → EAF transition**.
- Stay current with **API RP 751**, Shell MESC, and **MSS initiatives** (e.g., HF valve quality standards).

6.8 Role of Specialized Distributors – The BUHLMANN Group

The challenges outlined in this section — from melt-level residual control to traceability gaps in fittings and valves — make clear that HF alkylation metallurgy cannot be managed as a commodity. It requires a **specialized distributor** capable of bridging the gap between mills, EPCs, and refiners, while enforcing compliance at every stage.

Dedicated HF Materials Program

BUHLMANN Group is one of the few global PVF distributors with a dedicated HF program. Our portfolio is built specifically around HF-N metallurgy, covering:

- **Seamless Pipe, Flanges, and Fittings** — sizes ½–24”, pressure classes 150#–600#, all qualified to HF-N supplemental specifications.
- **Valves** — gate, globe, check, plug, and triple-offset butterfly valves, in HF-N steels and Alloy 400 for critical HF-1 and HF-2 services.

Certified Material Grades in Stock

BUHLMANN maintains inventory and supply agreements in the key HF-N product forms:

- ASTM A106 Gr. B S9 (pipe)
- ASTM A333 Gr. 6 S2 (low-temperature pipe)
- ASTM A234 WPB + A960 S78 (butt-weld fittings)
- ASTM A105 & A350 LF2 + A961 S62 (flanges/forgings)
- ASTM A516 Gr. 70 + S54 (plates for vessels and settlers)

These grades align with **API RP 751** and the chemistry restrictions referenced by **UOP HF piping classes**.

QA/QC Beyond Industry Standards

Because slight variations in Cu, Ni, or Cr can dramatically accelerate HF corrosion, BUHLMANN enforces a **multi-layered QA/QC program**:

- Dual chemistry verification (ladle + product).
- 100% PMI on high-risk components (fittings, flanges, valves).
- ERP-linked heat traceability from billet to delivery.
- Normalization and additional treatments via partnered forges when required by end-users.

In-House Forging & Machining Capabilities

Through subsidiaries such as **Unicorn and NRG Special Products**, BUHLMANN operates its own forging and machining facilities. This provides:

- Reinforced branch outlet fittings machined directly from HF-grade bar stock.
- Custom HF-N forgings for non-standard flanges and fittings.

- Small-batch production with full product analysis and normalization.

This vertical integration ensures metallurgy is controlled from billet through finished component — particularly valuable for fittings and valves, where traceability is weakest.

Proven Global Adoption

Refineries across Europe, North America, and the Middle East have already qualified BUHLMANN as a trusted supplier for HF units. Operators highlight two consistent advantages:

1. **Assured compliance** with Low RE chemistry requirements across multiple categories.
2. **Reduced procurement risk** during turnarounds, as critical components are already verified and in stock — not dependent on spot-market sourcing.

Strategic Value for HF Operations

The value of BUHLMANN lies not only in delivering compliant products, but in acting as a **quality gatekeeper for the entire supply chain**:

- Filtering out non-compliant heats before they reach the refinery.
- Providing PMI-backed documentation packages aligned with refinery QA/QC standards.
- Supporting engineering, procurement, and turnaround planning with unmatched material expertise.

By combining **inventory, vertical integration, and uncompromising QA/QC**, BUHLMANN eliminates uncertainty in HF metallurgy. For refiners, this translates to **safer operations, lower long-term risk, and complete confidence in compliance**.

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7. Quality Assurance & Quality Control (QA/QC)

Securing HF-N materials through purchase specifications is only part of the solution. The greater challenge is **verifying compliance across the supply chain**. Industry incidents have shown that even when documentation appears correct, residual element levels can exceed HF limits — leading to leaks, failures, and severe safety risks. A robust QA/QC framework is therefore essential for HF alkylation metallurgy.

7.1 Dual Chemistry Verification

Residual element control must be confirmed at both the **ladle analysis** (during steelmaking) and the **product analysis** (on the finished component).

- **Ladle analysis** validates compliance at the melt stage.
- **Product analysis** ensures residuals did not drift during downstream processing.

BUHLMANN requires dual chemistry results for every HF-N heat and **rejects any material failing either dataset**.

7.2 100% PMI on High-Risk Items

Fittings, flanges, and valves are the categories most vulnerable to substitution or mislabeling. For these items, **100% Positive Material Identification (PMI)** is mandatory.

- Advanced portable XRF/OES analyzers are used, capable of detecting Cu, Ni, and Cr down to 0.01%.
- This eliminates the risk of incorrect alloys entering HF service.

7.3 Traceability & Documentation

Every HF-N component must remain fully **traceable from billet to refinery delivery**. BUHLMANN's ERP-linked system ties together:

- Heat numbers
- MTRs (Mill Test Reports)
- PMI results
- Normalization and treatment records

The result is a **complete quality dossier** for each order, ensuring refiners can demonstrate compliance during audits or regulatory inspections.

7.4 Independent Testing & Oversight

For high-value or critical orders, **independent laboratories and third-party inspectors** are engaged to verify chemistry, mechanical properties, and weld procedures. This adds an **extra layer of assurance** beyond distributor or mill certification.

7.5 Industry Lessons

Past HF unit incidents have revealed a recurring theme: **paperwork was correct, but chemistry was not.** These failures underscore that QA/QC cannot stop at documentation. Compliance must be **verified, not assumed**.

7.6 BUHLMANN's QA/QC Differentiator

BUHLMANN Group enforces QA/QC protocols that exceed standard industry practice:

- Dual chemistry (ladle + product) on every HF-N heat.
- 100% PMI for fittings, flanges, and valves.
- ERP-linked heat traceability for full audit readiness.

- Independent verification for critical projects.
- Normalization and treatments via partnered qualified producers where required.

This rigorous approach positions BUHLMANN not only as a supplier, but as a **quality gatekeeper for the HF supply chain**. Our customers receive materials that are not just certified, but **proven to be compliant, safe, and reliable**.

8. Future Outlook

The global supply chain for HF alkylation metallurgy is undergoing structural change. The transition from ore-based BF–BOF to scrap-based EAF production has permanently altered the availability of Low Residual Element steels. Refiners can no longer assume compliance by default; they must secure it deliberately at the melt stage and enforce it rigorously through QA/QC.

Looking ahead, several trends will define the next decade of HF alkylation supply:

8.1 Steelmaking Transition

The global steel industry will continue shifting toward **EAF scrap-based production** in response to cost, capacity, and sustainability drivers. This trend will likely increase residual element challenges, pushing refiners and licensors to tighten specifications further.

8.2 Evolving Standards

Industry bodies such as **API, NACE, and MSS**, along with licensor specifications (e.g., **UOP, ConocoPhillips, Shell MESC**), are expected to update requirements to reflect these challenges. Stricter cumulative residual limits, mandatory dual chemistry, and expanded QA/QC protocols are likely outcomes.

8.3 Digitalization of QA/QC

Advances in digital traceability, including **ERP-linked databases, blockchain certification, and real-time PMI logging**, will increasingly become the standard for ensuring compliance and audit readiness across global supply chains.

8.4 Supply Chain Consolidation

As fewer producers can consistently meet HF-N requirements, refiners will depend more heavily on **specialized distributors** with the ability to aggregate demand, coordinate melt campaigns, and apply additional treatments across product categories.

8.5 BUHLMANN's Role in the Future

In this evolving landscape, **BUHLMANN Group is positioned not just as a supplier, but as a strategic partner** in HF alkylation metallurgy. By combining:

- Long-term relationships with qualified mills and producers,
- A global inventory program aligned with HF-N specifications,
- In-house forging and machining capabilities, and
- A multi-layered QA/QC system that exceeds industry practice,

BUHLMANN ensures that refiners can navigate uncertainty with confidence.

As the industry shifts, one constant will remain: **safe HF alkylation depends on uncompromising metallurgy.** BUHLMANN's mission is to deliver that assurance — today and in the decades to come.

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9. Conclusions & Recommendations

The HF alkylation process is one of the most demanding environments in refining, and its safe operation depends directly on the integrity of Low Residual Element (HF-N) metallurgy. The industry no longer benefits from the natural compliance of ore-based steelmaking. With the shift toward EAF scrap-based production, refiners must take a proactive, strategic approach to ensure materials meet HF-specific requirements.

Three key conclusions emerge from this study:

1. **Compliance cannot be assumed.** Residual element limits defined in ASTM supplemental clauses (A106 S9, A333 S2, A960 S78, A961 S62, A516 S54) must be explicitly specified and verified.
2. **Supply chain risk is uneven.** Seamless pipe remains accessible with planning, but fittings and valves — especially butt-weld fittings and large cast/forged valves — represent the highest procurement and compliance risks.
3. **QA/QC is the decisive factor.** Paperwork alone is insufficient. Dual chemistry verification, 100% PMI, and full traceability are essential to preventing non-compliant materials from entering HF service.

Recommendations for Refiners and EPCs

- **Plan Early:** Secure melt campaigns and specialty items 12–24 months before turnarounds.
- **Specify Clearly:** Reference ASTM HF-N clauses and cumulative residual limits in all contracts.
- **Prioritize High-Risk Items:** Allocate budget and lead time for fittings and valves.

- **Adopt Rigorous QA/QC:** Require dual chemistry, PMI, and traceability dossiers from suppliers.
- **Partner Strategically:** Work with distributors that combine inventory, technical expertise, and independent QA/QC oversight.

BUHLMANN Group has built a dedicated HF program to meet the growing challenges of residual element control and supply chain risk. By aligning **global inventory, vertical integration, and uncompromising QA/QC**, we act not only as a supplier but as a **strategic partner**. The result is more than compliant materials — it is **confidence in metallurgy and safer, more reliable HF alkylation operations worldwide**.

10. References

10.1 Standards & Codes

- ASTM A106/A106M – 19a: *Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service* (including Supplementary Requirement S9).
- ASTM A333/A333M – 18: *Standard Specification for Seamless and Welded Steel Pipe for Low-Temperature Service* (including Supplementary Requirement S2).
- ASTM A516/A516M – 17: *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service* (including Supplementary Requirement S54).
- ASTM A960/A960M – 20: *Standard Specification for Common Requirements for Wrought Steel Piping Fittings* (including Supplementary Requirement S78).
- ASTM A961/A961M – 21: *Standard Specification for Common Requirements for Steel Flanges, Forged Fittings, Valves, and Parts* (including Supplementary Requirement S62).

10.2 Licensor & Industry Guidelines

- API Recommended Practice 751 (9th Edition, 2021): *Safe Operation of HF Alkylation Units*.
- UOP (2015): *Piping Specifications for HF Alkylation Units*.
- Shell MESC Specifications: *HF Alkylation Materials Guidance*.
- ConocoPhillips Licensing Documentation: *HF Alkylation Metallurgy Recommendations*.

10.3 Technical Papers & Training Materials

- Becht Engineering (2018): *HF Alkylation Training – Public Edition*.
- NACE Paper No. 03651 (2003): *Control of Residual Elements in Carbon Steel for HF Alkylation Units*.

Appendix: Figures

List of Figures

Figure 1. HF Alkylation Process Flow Diagram

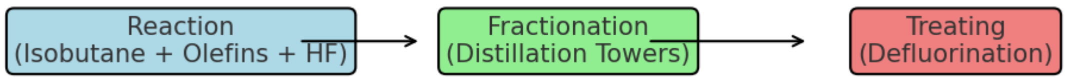


Figure 2. Metallurgy Selection Map

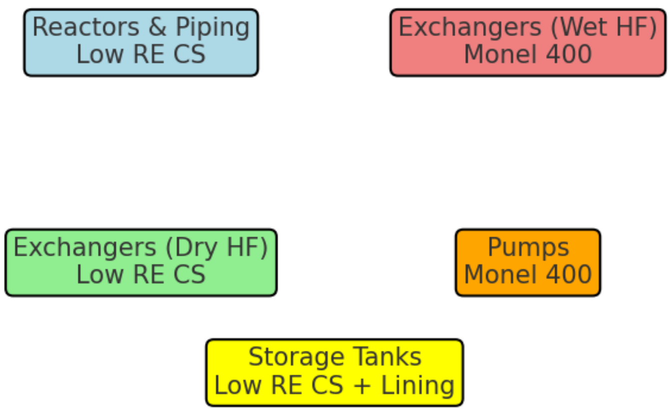
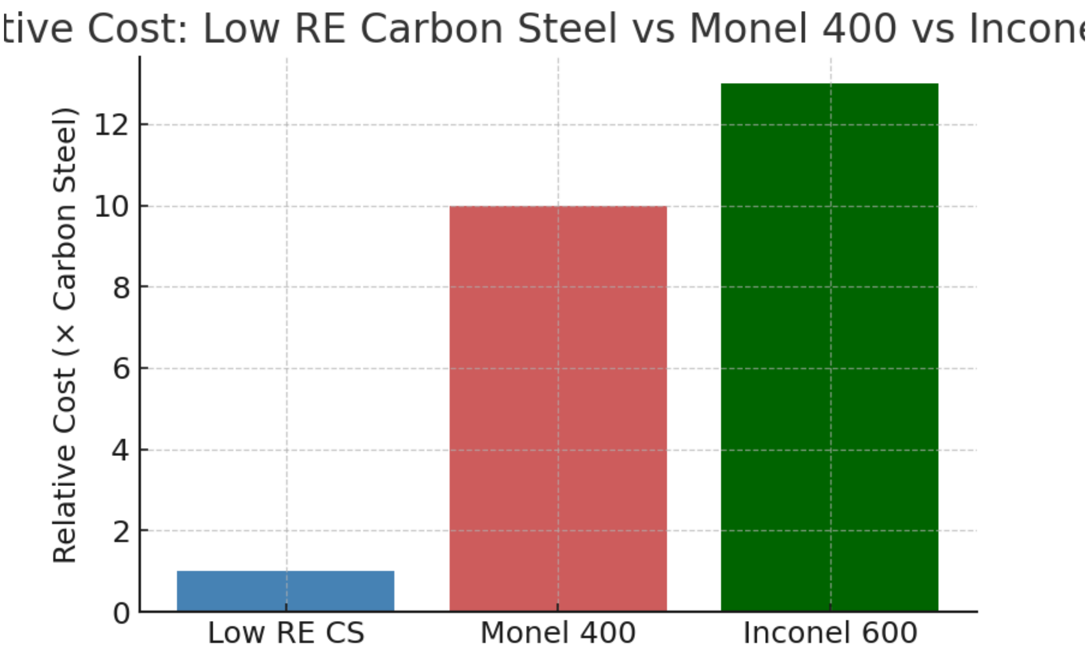
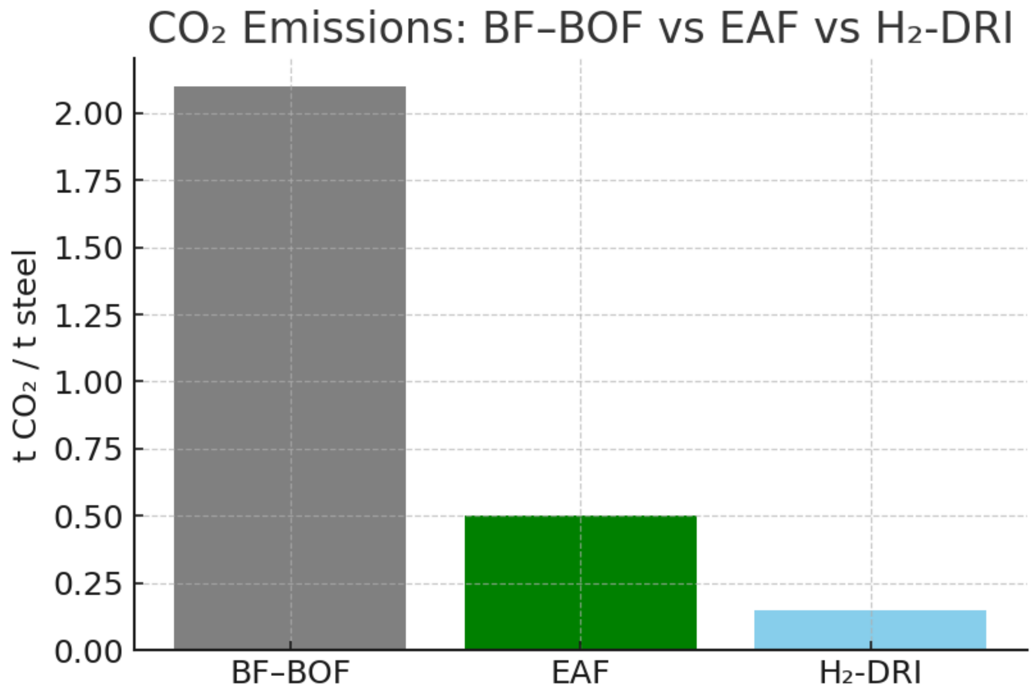


Figure 3. BF–BOF vs EAF Steelmaking Schematic




CO₂ Emissions: BF–BOF vs EAF vs H₂-DRI
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2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
BF–BOF
EAF
H₂-DRI