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Negative-Side Collector & Interlayer Trade-offs for Interface-Zone Stability (Stack-Agnostic Brief)

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1. Summary

At-a-Glance: Negative-side current collectors span metals (and their alloys), carbon-based foils, polymer laminates, and hybrids – each with distinct trade-offs in electrical conductivity, mechanical strength/flexibility, environmental stability, and manufacturability. Table 1 summarizes key properties and selection cues for major collector families (with typical thickness ranges). In essence, **copper (Cu) remains the benchmark** for high conductivity (bulk resistivity ~1.7 µΩ·cm) [1], balanced ductility, and well-understood interface behavior, but its oxide layer can raise interfacial resistance [2]. **High-strength Cu alloys** sacrifice some conductivity (e.g. ~86% of Cu's conductivity) for up to 50–100% higher tensile strength [3], aiding stability with expansive anodes (e.g. Si) at the cost of more resistance and expense. **Aluminum (Al)** offers low density and cost with ~60% the conductivity of Cu [4], but is traditionally limited to positive electrodes due to lithium-alloying risk at low potentials. **Nickel (Ni)** and **stainless steel** foils provide exceptional mechanical strength and corrosion resistance, tolerating thin gauges <10 µm [5] and harsh environments, but have 4–10× higher resistivity than Cu [6] [7] – making them suitable only where currents are lower or where chemical stability outweighs electrical losses. **Carbon fiber papers/cloths** and emerging **conductive polymers** eliminate metal corrosion and are ultra-lightweight, yet their conductivities are orders of magnitude lower than metals (e.g. carbon papers ~10^3–10^5 S/m vs Cu ~5.8×10^7 S/m) ⑧. Such non-metallic collectors are thus limited to specialty applications (flexible or structural batteries) requiring modest currents. **Composite laminates** (metal-polymer hybrids or clad foils) aim to combine metal conductivity with polymer weight or safety advantages, but introduce manufacturing complexity and temperature limits (polymer softening). **Surface-engineered foils** – e.g. carbon-coated Cu or Sn-plated Cu – are not separate families per se but critical enhancements: they reduce contact resistance ⑨, improve lithium wettability and dendrite suppression ⑩, and add corrosion barriers without changing the bulk collector dimensions.

When to Consider Each: Use **pure Cu collectors** for most high-rate negative electrodes (graphite, Li-metal, etc.) where low electrical impedance is paramount and standard processing (slitting, welding) is established. Opt for **high-tensile Cu or Cu–Ni alloy foils** when the negative-side stack (NSS) active material undergoes large volume changes (e.g. Si anodes), or when operating temperatures and pressures are above Cu's softening range – these alloys retain strength up to 250–300 °C ⑪ and mitigate anode expansion at some cost in conductivity ③. Choose **Ni or stainless steel collectors** in niche cases demanding ultra-thin foils with extreme durability or inertness – for example, lithium titanate anodes (which operate at ~1.5 V vs Li, avoiding Li-Al alloying) sometimes use stainless or Ni to exploit their stability ⑤. **Aluminum foils** may be considered on the negative side only for chemistries that never approach 0 V vs Li (to prevent alloying) – e.g. LTO anodes or certain solid-state designs – leveraging Al's light weight and cost, but one must manage its native oxide and lower modulus. **Carbon-fiber or polymer current collectors** are viable for flexible or weight-critical designs where current densities are low and cells can tolerate higher internal resistance; they shine in eliminating metal corrosion and in providing flexibility that metals cannot (e.g. carbon fiber collectors survive repeated bending with minimal fatigue) ⑫. **Metal-polymer laminate collectors** (such as thin Cu on polyimide film) are useful for improving puncture safety and dielectric isolation in the interface zone (IZ), or in bipolar battery architectures (e.g. Cu-Al cladded foils for integrated series stacking) ⑬, but their multi-layer nature complicates welding and raises interface resistance unless carefully engineered. Lastly, **coated/surface-treated foils** should be seen as an enabling enhancement for many scenarios: a thin carbon coating on Cu or Al can **dramatically lower contact resistance** (e.g. a drop from ~200 to 40 $\Omega\cdot\text{cm}^2$ area-specific resistance when using carbon-coated Al vs bare Al) ⑨, while metal coatings like Sn or Ag can promote uniform lithium plating and suppress dendrites on a Cu collector ⑩ ⑭. In practice, pairing the right **collector family** with appropriate **interlayer coatings** and quality processing (edge finishing, etc.) is critical to achieving a stable, low-impedance interface zone over the cell's life.

Table 1 – Summary of Collector Families and Trade-offs (Negative Side)

Family	**Examples / Composition**	**Electrical** (Conductivity & Resistivity)	**Mechanical** (Strength & Flexibility)	**Thermal** (CTE & Temp. Limits)	**Environmental** (Corrosion & Stability)	**Typical Gauge** (µm)
Copper (Cu) Foils	High-purity Cu (rolled or ED)	**Excellent:** ~59 MS/m (100% IACS), ρ≈1.7 µΩ·cm ① . Sheet R ≈1.5–2 mΩ/□ @10 µm.	**Ductile;** tensile ~300–400 MPa in thin RA foil ⑮ (up to 400 MPa hard limit ⑮). Bends to few-mm radius (good for winding).	CTE ~16–17 ppm/K (moderate mismatch to ceramics). Melting 1085 °C; softens >150 °C (HT grades up to 180 °C) ⑯ .	Oxidizes (CuO) in air ② ; **stable in NSS** (no self-alloying). Needs dry processing to avoid CuO forming high contact resistance ② .	6–12 µm common (down to ~4–5 µm advanced) ⑰ ; widths up to ~1200 mm (ED) ⑰ .
High-Tensile Cu Alloys	Cu–Ni, Cu–Ti or proprietary alloys (RA foil)	**Very good:** 40–90% IACS depending on alloy (e.g. 86% IACS at 500–600 MPa ③ ; ~40% IACS at 750 MPa ⑱). ρ≈2–4 µΩ·cm.	**High-strength:** up to 500–750 MPa UTS ⑲ , with reduced elongation. Still fairly ductile (≤15% strain). Maintains strength to 250–300 °C ⑪ . Slightly less flexible (alloying can reduce elongation).	CTE similar to Cu (≈15–17 ppm/K). Can withstand higher temp processing (some alloys stable to 300 °C) ⑪ .	Similar oxidation behavior to Cu (surface tarnish). Alloying elements may form their own passive films (e.g. NiO) – generally stable in battery environment. No Li alloying issues.	8–20 µm (min ~10 µm due to rolling limits ⑳). Specialty product (limited suppliers).

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Aluminum (Al) Foils	1xxx or 3xxx-series Al (battery-grade)	**High:** ~37 MS/m (≈63% IACS), $\rho \approx 2.7\ \mu\Omega \cdot \text{cm}$ ④ . About 2× Cu's resistivity. Still low sheet resistance (e.g. ~3.4 mΩ/□ @10 µm).	**Soft & ductile:** tensile ~70–150 MPa (annealed foil), high elongation (>10%). Easy to bend or wrinkle. Lower yield strength than Cu, but work-hardens if rolled.	CTE ~23 ppm/K (higher mismatch; significant expansion). Melting 660 °C; withstands ~150 °C long-term (above that, loses strength).	Instant oxide (Al_2O_3) layer gives **excellent corrosion resistance** in air and cathode environments ② . **Not used in NSS with Li metal** – Al alloys with Li below ~0.2 V (risk of disintegration). Stable for anodes that stay >0 V (e.g. LTO).	10–20 µm typical (cathode foils). Thinner (~5–10 µm) under R&D for weight savings.
Nickel (Ni) Foils	Pure Ni (rolled or electroformed)	**Moderate:** ~15 MS/m (26–29% IACS), $\rho \approx 6\text{–}7\ \mu\Omega \cdot \text{cm}$ ⑥ . 3–4× higher resistivity than Cu. Sheet R ~5 mΩ/□ @10 µm.	**Strong:** hard-rolled Ni: 620–790 MPa UTS ㉑ . Annealed ~450 MPa ㉒ . Low elongation when hard (1% at 10 µm thick ㉓), but can be made ductile by anneal (≥15% elongation at 50 µm ㉔). Good springiness; can be very thin via electroform.	CTE ~13 ppm/K (closer to ceramic SSE than Cu). Melting 1455 °C; retains strength well up to ~300 °C.	Forms stable NiO surface in moist air; **high corrosion resistance** in alkaline or low-moisture cells ㉕ . Can serve as collector for both NSS and SES sides ㉕ . No Li alloying; Ni is lithiophobic (but can catalyze certain SEI components).	5–20 µm available (electroformed Ni can be made ~10 µm with smooth finish ㉖ ㉗). Widths typically ≤500 mm ㉘ .

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Stainless Steels	Fe–Cr–Ni alloys (e.g. 304, 316)	**Low to moderate:** 0.7–6 MS/m (1–10% IACS) depending on grade [7] ; ρ ~20–80 µΩ·cm typical. Much higher resistance per area (e.g. 18 mΩ/☐ @10 µm for ρ=18 µΩ·cm).	**Very high strength:** many SS foils 600–1000 MPa (e.g. full hard 304 ~900 MPa). Can be made extremely thin (<10 µm) by deposition or etching [5] . Less bendable (lower elongation ~2–10%). Can add perforations (mesh) to improve flex and reduce weight [29] .	CTE ~10–17 ppm/K (depends on alloy, e.g. 304 ~17). Good thermal stability: usable up to 250 °C continuously (no creep in normal battery temp range).	**Outstanding corrosion resistance:** self-passivating Cr_2O_3 film [5] makes it resistant to moisture, air, many electrolytes. Tolerates both **neutral and basic environments** [5] . No reaction with Li metal (aside from superficial plating).	5–20 µm (ultra-thin feasible due to strength). Often used as mesh or foam for better utilization [29] .

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Carbon-Based	Carbon fiber paper; woven carbon cloth; CNT mats	**Poor (vs metals):** bulk in-plane conductivity can range 10^3–10^5 S/m [30] (effectively <1% IACS). Through-plane much lower. High sheet resistance unless thick or metal-coated.	**Flexible, not strong:** fiber papers have tensile strength tens of MPa (e.g. ~30 MPa [31]). Can flex indefinitely without metal fatigue. Thickness provides some cushioning. Low density (~1.5–2.0 g/cc). Can tear if handling improperly (brittle fibers).	CTE negligible along fibers (carbon ~0 ppm/K); but composite structure with binder may expand. Can usually tolerate wide temps until binder or surface treatments decompose (> 150 °C if polymer-bound).	**Chemically inert** (no metal corrosion). Stable against most electrolytes, but will oxidize if exposed to strong oxidizers or >300 °C air. Forms stable SEI (graphitic surface) in NSS environment. No self-passivation needed.	50–300 µm (papers) with porosity 70–90%. Often used as 3D scaffold rather than pure collector in thin form. Tricky to make <50 µm continuous sheets due to fiber diameters.

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Metal–Polymer Laminates	e.g. Cu or Al foil laminated to polyimide film; Cu–PE foil; Al–Cu clads	**Variable:** depends on metal layer thickness – a thin metal on polymer has higher sheet resistance. (e.g. 5 µm Cu on film: ~3 mΩ/□). Polymer is insulating except providing a barrier.	**Laminated properties:** polymer provides tear resistance and flexibility (no metal fatigue); metal provides some strength but overall tensile lower than pure foil of same thickness. Typically not used for structural support, more for safety (e.g. prevents propagation of tear).	Polymer layer limits max temperature (e.g. polyimide up to ~120–180 °C). CTE of polymer (~20–50 ppm/K) can cause differential expansion with metal. Some designs use low-CTE polymer to mitigate.	Polymer layer adds **moisture/chemical barrier**, protecting metal from direct exposure. However, if edges are exposed, metal can still corrode at edges. Generally, polymer prevents dendrite penetration in some concepts (acts as partial insulator around metal).	20–50 µm total (e.g. 5–10 µm Cu + 15 µm polyimide). Often custom-made; used in special cell designs (flex circuits, bipolar electrodes ⑬).

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Coated / Surface-Treated	(Not a separate base material – thin coatings on above foils) Carbon-coated Cu or Al; Sn-, Ag- or Au-plated Cu; oxide layers (ALD Al_2O_3); polymer-coated metal	**Base metal governs bulk conductivity.** Thin conductive coatings (carbon, metals) have negligible thickness (nm–µm) – they slightly reduce cross-sectional area if non-conductive (oxide/polymer). Overall electrical effect is reducing contact resistance rather than bulk resistivity.	**Mechanical:** Coatings typically add no significant stiffness (too thin), but can improve handling (e.g. polymer coat reduces foil burrs). Some brittle ceramic coatings (oxides) may crack under flexing – so use on already flexible substrates is limited.	**Thermal:** Most metallic and carbon coatings handle battery processing temps. Polymer or Li-containing interlayers may have specific temp limits (e.g. polymer binders <150 °C). ALD oxides stable to very high temp but can create thermal stress if CTE-mismatched.	**Interface/ environment:** Coatings often serve as **barrier** (prevent direct metal contact with electrolyte) ㉜ or **wettability promoter** (e.g. lithiophilic metal to guide plating) ⑩. Carbon coatings remove native oxides ㉝ and dramatically lower interfacial impedance (5× reduction in contact $\Omega \cdot cm^2$) ⑨. Many coatings also inhibit corrosion (e.g. ALD Al_2O_3 on Cu raises polarization resistance by 100× in saltwater tests ㉞ ㉟).	Thickness impact: Carbon coatings typically ~1–5 µm ㊱ (e.g. PVDF/carbon layers), ALD/PVD coatings ~5–50 nm, metal platings ~100 nm to few µm. These add negligible thickness to ~10 µm foils but must be uniform. Coatings require extra processing (cost/tracks).

Key: IACS = % conductivity relative to International Annealed Copper Standard; ρ = bulk resistivity; CTE = coefficient of thermal expansion; UTS = ultimate tensile strength; NSS = negative-side stack; SEI = solid-electrolyte interphase. Data ranges reflect room-temperature values unless noted. Sources: [1]–[9]. (See Appendix for detailed data and sources.)

2. Scope & Definitions

Objective: This brief addresses the **trade-offs among negative-side current collectors and interlayers** for lithium-based battery stacks, without assuming any specific cell chemistry, collector metal, solid vs. liquid electrolyte, or joining method. It is “**stack-agnostic**,” meaning the guidance should hold whether the interface is e.g. a lithium-ion anode with liquid electrolyte and separator, or a lithium-metal electrode in contact with a solid electrolyte. All discussions are **chemistry-neutral within the realm of Li-ion/Li-metal batteries** (no particular electrode active material is presumed). Where necessary, the negative side of the cell is referred to generally as the **"negative-side stack (NSS)"**, and the separator or solid electrolyte side as the **"solid-electrolyte-side stack (SES)"** – emphasizing the interface zone between them (the **"interface zone (IZ)"**). For example, the IZ could be the thin region where a Cu current collector, its coating (if any), the solid-electrolyte surface, and any interphasial films come together. By remaining assumption-free about direct contact vs. laminated interfaces, this brief covers both conventional foil-to-coated-electrode interfaces and novel stacked architectures (laminated, bipole, etc.).

Definitions:

- **Current Collector (Negative Side):** A conductive layer (foil, foam, mesh, etc.) that serves as the electron-conducting substrate for the NSS. This can be a metal (Cu, Ni, Al, steel, etc.), carbon-based material, or composite. It typically does not participate electrochemically except to conduct electrons and sometimes alloy with lithium (which is usually undesired except in certain designs).
- **Interlayer / Coating:** Any engineered material layer between the bare collector substrate and the adjacent stack component (active material or electrolyte). Interlayers can be carbon coatings, polymer binders, metallic platings, oxides, etc., applied to enhance interface stability. Here we consider interlayers on the **negative side** only (e.g. a protective coating on a Cu foil, not cathode Al foil coatings).
- **Interface Zone (IZ):** The region encompassing the collector surface, any coatings, plus the immediate contact area with the SES (which might be an electrode coating or a solid electrolyte surface). Stability here refers to mechanical, electrical, and chemical stability over cycling.
- **J/C Compatibility:** Shorthand for **joining/coating compatibility** – essentially how well a collector material can be joined (welded, soldered, laminated) or accept surface coatings/treatments. For instance, a given collector must be compatible with tab welding processes (joining) and also with any required coating deposition processes (plating, sputtering, etc.) without degrading.
- **Trade-offs Criteria:** We evaluate collectors on multiple criteria: **Electrical** (conductivity, contact resistance), **Mechanical** (tensile strength, elongation, bending tolerance), **Thermo-Mechanical** (thermal expansion, creep at operating pressure), **Environmental** (corrosion in presence of electrolyte or moisture, stability against reactions), **Manufacturability** (available thickness/width, surface uniformity, ease of handling and slitting), and **Cost/Availability** (relative material cost and supply chain maturity). Wherever possible, quantitative units are given (e.g. resistivity in $\mu\Omega\cdot$cm, tensile strength in MPa, etc.) and are drawn from primary sources or standardized references. Regional nuances (e.g. standards or typical practices in Japan vs. EU vs. US) are noted when relevant – though most technical metrics are global.

This report emphasizes **evidence-based** comparisons. All data are cited from reputable sources: standards, peer-reviewed papers, authoritative handbooks, or industry technical reports. In cases where sources disagree (measurement conditions, purity, etc.), a range is reported with context. All handling or safety discussions remain generic and refer to public standards – **site-specific safety protocols always override** any general guidance given here.

3. Collector Families

Different **collector families** are used (or proposed) for negative electrodes, each with unique advantages and drawbacks. Below, we compare the major families: **(3.1) Metals and Alloys**, **(3.2) Carbon-based**, **(3.3) Metal–Polymer Composites**, and **(3.4) Surface-Treated Foils**. The focus is on how each type balances electrical performance, mechanical integrity, environmental stability, and manufacturability.

Table 1 (above) provides a summary, and a more detailed property table is provided in the Appendix (Table A1) for reference.

3.1 Metals & Alloys (Cu, Ni, Fe–Ni, Al, Stainless)

Metals are the workhorse current collectors due to their high electrical conductivity. On the negative side of Li-ion cells, **copper (Cu)** foil has been the industry standard for decades [37], thanks to its excellent conductivity (~1.7 µΩ·cm resistivity) and adequate mechanical properties. **Aluminum (Al)** foil, while even lighter and almost as conductive (2.7 µΩ·cm), is normally used only on the positive side because it would alloy with lithium at low potentials (rendering it unusable for graphite or Li-metal anodes) [38] [39]. However, Al can function as a negative collector in special cases (e.g. with lithium titanate anodes that operate at ~1.5 V vs Li, safely above Al–Li alloying thresholds). **Nickel (Ni)** and **stainless steel** are alternative metal collectors that offer higher strength and corrosion resistance; they have been explored in both academia and niche products where Cu's properties fall short (for instance, some solid-state or high-temperature cells) [40] [25]. We also include **Fe–Ni alloys** (e.g. Invar, a 36% Ni steel) in this family – these materials have specialty uses due to very low thermal expansion, albeit at the cost of extremely high resistivity (~80 µΩ·cm for Invar) [41] [42].

Copper (Cu) Foils – Baseline: Copper's ~60 MS/m conductivity (IACS 100%) means a thin foil (10 µm) has sheet resistance on the order of 1–2 mΩ per square [43]. This low in-plane resistance minimizes ohmic losses even for high-current pulses. Cu is also readily available in battery-grade foil form: common thicknesses are 8–12 µm for commercial 18650/2170 cells, with advanced designs using 6 µm or even 4 µm to save weight (though handling becomes more delicate) [17] [44]. Two production methods exist – **rolled annealed (RA)** and **electrodeposited (ED)** copper foil – each with subtle differences. RA foil is smoother and more ductile (having a uniform crystal structure), whereas ED foil has a matte side and can achieve ultra-thin gauges by electrolytic deposition [45]. RA foils can incorporate alloying (ED typically cannot, being pure Cu) [45]. Mechanical properties of Cu foil depend on processing: fully annealed Cu is very soft (yield strength ~70–100 MPa), but in thin foils that have been work-hardened, the tensile strength can approach 300–400 MPa [15]. Indeed, ~400 MPa is cited as the practical upper strength for pure Cu in thin foils [15]. Cu's flexibility is good – it can be bent to a few-millimeter radius without cracking, especially in RA form. However, Cu foils under tension can tear if defects or nicks are present (hence slitting quality is critical, see § 5). Thermally, Cu's expansion (CTE ~16 ppm/K) is higher than that of ceramics or solid electrolytes, which can induce stress if a Cu-collector cell is heated or cycled in temperature. Cu's melting point (1085 °C) is far above any battery operation, but at elevated temperatures (>150 °C) Cu will oxidize rapidly and soften (anneal). In normal cell use (−20 to 60 °C), Cu is stable; **its main drawback is propensity to form an oxide layer** even at room conditions (tarnish). That oxide (CuO/Cu_2O) can increase the interfacial resistance between the Cu and the electrode coating [2]. Consequently, manufacturers handle Cu foils in dry rooms and sometimes employ **carbon coatings or treatments** to mitigate oxide effects (discussed in § 3.4 and § 4). Cu does not alloy with lithium under typical negative electrode potentials (0–0.5 V vs Li^+/Li), which is why it safely serves as the anode collector in Li-ion cells (in contrast, if lithium metal is directly plated on Cu, it will not destroy the Cu – it simply deposits Li, which can later be stripped). However, **dendrite growth** can occur on Cu if lithium plating is non-uniform; coatings like Sn have been proposed to guide uniform Li deposition on Cu and avoid dendritic protrusions [10].

High-Tensile Copper Alloys: To address the relatively low yield strength of pure Cu, especially under the large volume changes of next-gen anodes (silicon, etc.), researchers and companies have developed Cu-based alloys for foils. Examples include Cu–Ni and Cu–Ti alloys among others. SCHLENK, for instance, markets **High Tensile Alloy (HTA)** foils where tensile strengths of 500–750 MPa are achieved (vs ~300 MPa for standard Cu) [46] [19]. The trade-off is a reduction in conductivity: one alloy at ~600 MPa was ~86% IACS (resistivity ~2.0 µΩ·cm) [19], and pushing to 750 MPa roughly halves the conductivity (~40% IACS)

[18]. These alloys often include a few percent of Ni, Sn, or other elements that solid-solution strengthen the copper. They maintain good conductivity compared to other metals (even 40% IACS is still better than stainless steel by a large margin) but will generate more Joule heating at high currents. A key benefit besides strength is **thermal stability**: high-tensile Cu alloys can retain their strength at higher temperatures. Whereas pure Cu foil might start to relax or creep around 150–180 °C, some HTA foils are stable up to 250–300 °C [11], which can be crucial for processes like solvent drying or calendaring of Si-rich anodes (or for emerging cell designs that involve heat). These foils are also reported to better withstand the pressure of volume-changing anodes without elongating or tearing [44]. **Use cases:** If an anode (NSS) swells significantly (e.g. 100% volume swings for Si) and exerts stress on the collector, an HTA foil can help maintain contact and reduce wrinkling or delamination. They are also considered for solid-state batteries where the stack may be pressed at elevated temperature – the foil needs to not creep under the stack pressure. One must weigh cost and availability: such alloys are more expensive and may be proprietary; they are typically rolled in small quantities (battery-grade pure Cu foil, in contrast, is a commodity). Nonetheless, their vendor-neutral value is demonstrated in literature: e.g., a Cu–0.3%Ti alloy foil showed ~2× higher 0.2% yield strength than pure Cu with only ~10% conductivity drop [47] (strength ~500 MPa vs 250 MPa for Cu, conductivity 90% vs 100% IACS). These alloys still oxidize similarly to copper (primarily CuO, possibly with dopant oxides), so surface protection remains important.

Aluminum (Al) Foils: Aluminum's role on the negative side is limited but worth noting. As the standard cathode collector, Al is inexpensive and light (density 2.7 g/cc vs Cu's 8.9) and forms a stable oxide that protects it at high potentials [48]. On a negative electrode, however, if the potential of Al drops close to 0 V vs Li, **aluminum will alloy with lithium** (forming Li–Al compounds) causing the foil to become brittle or even disintegrate. Thus, in a typical lithium-ion cell that uses a carbonaceous anode which can go to ~0 V vs Li, Al cannot be used – copper is chosen instead [38]. However, if the negative electrode operates at a higher voltage (for instance, lithium titanate ~1.55 V or certain oxide anodes), Al foil has been demonstrated as a viable collector [25]. The benefit is a ~50% mass reduction of the collector (important for specific energy) and cost reduction. Al's conductivity is ~63% of Cu's; this still yields low sheet resistance in thin foils (an 15 µm Al foil has ~the same resistance as a 10 µm Cu foil, since resistivity ratio ~1.6× but thickness 1.5×). Mechanically, Al is very ductile (elongation often >10%) and forgiving to bend (it has a lower elastic modulus ~70 GPa, so it's more compliant). But its yield strength is low, and it can't sustain much tension before necking – hence pure Al foils are more prone to edge wrinkling and tearing during winding if not handled carefully. Notably, battery Al foils are often electrochemically etched to have a rough surface (to improve cathode active adhesion) [49]; on the negative side, such etching could be used too, but one must be cautious: a rough Al foil on the negative might have high surface area which, if any lithium plating occurs, could exacerbate reactivity. **Corrosion-wise**, Al forms Al_2O_3 instantly which actually **helps** in many cases (protecting it from HF or moisture attack) [48]. But if that oxide breaks (either mechanically or by a chemical complexing, e.g. by F^- forming AlF_3), Al can corrode. For example, if a water-based anode slurry directly contacts Al, it can corrode the foil (since Al oxide is amphoteric and dissolves in high-pH conditions) [50]. One study found significant corrosion of Al foil when a basic LiNiCoMnO_2 cathode slurry (with water binder) was cast on it, whereas a carbon-coated Al foil was immune [50]. This underscores that **surface coatings can extend Al's usability** in unusual environments (including possibly on the negative side with protective layers). In sum, Al collectors on NSS are rare in commercial cells but might appear in specialized designs; whenever used, coatings (carbon, etc.) and potential constraints are employed to avoid direct Al–Li interaction.

Nickel (Ni) Foils: Nickel has a long history in battery tech (e.g. Ni-based batteries, Ni foam in NiMH cells). For lithium batteries, Ni foil is of interest primarily for lithium metal anodes and solid-state batteries. Ni's conductivity (~6.4 µΩ·cm resistivity) is significantly lower than Cu's, but still a good conductor (better than most alloys or any non-metal). Pure Ni foil is also mechanically robust: as shown in Table 1, electrodeposited hard Ni foil can reach >700 MPa tensile strength in 10–20 µm thickness [22] [23]. It is also relatively resistant to deformation at cell-stack pressures. These traits are useful if the negative electrode is lithium metal: Ni does not alloy with Li (except at extremely elevated temperatures where intermetallics might form, but not under normal cell conditions). Lithium will plate onto Ni surfaces, although Ni is not as “lithiophilic” as some other metals (meaning Li might plate in a more dendritic form unless the Ni surface is treated). Some researchers use Ni foil as the current collector for anode-free cells (where Li is plated onto the collector from the first cycle) – the Ni offers a stable, high-melting substrate that can handle the plating/stripping without dissolving, unlike Cu which can develop Li–Cu alloy at the interface at elevated temperature (Cu and Li do not form alloys at room temperature, but some reports suggest at moderate heating or over long times a small amount of Cu can dissolve into Li). In any case, Ni’s passivation is simpler: it forms a thin NiO that adheres well and actually **protects against further corrosion** in many electrolytes [25]. Ni is known for good stability in both acidic and alkaline environments [25], which translates to being fairly inert in typical carbonate or ether electrolytes (aside from the surface oxide). If moisture is present, Ni can slowly form Ni(OH)_2, but in a sealed cell that’s not an issue. One downside of Ni is density (~8.9 g/cc, like Cu) and cost – Ni is generally more expensive than Cu per kg, and high-purity thin Ni foils are not as mass-produced. Still, for niche uses, Ni foil has been made as thin as 5–10 µm (often by electroforming, which yields a very smooth, pure product) [28] [27]. The electroforming process allows continuous production of thin Ni with one polished side (cathode side) and one matte side (like ED Cu). Such foils may have applications in solid-state batteries where a sintered sulfide or oxide electrolyte might be pressed onto the collector – Ni’s hardness could help maintain contact. Also, Ni foil can serve as a **bi-functional current collector** in some experimental cells: because Ni is stable at positive potentials too, it has been tested as both anode and cathode collector (unlike Cu which cannot go to ~4 V without dissolving, Ni can, though with higher resistance) [25]. That could simplify cell design (one metal for both sides) in special cases, though at a performance penalty.

Stainless Steel: Stainless steel foil (typically austenitic stainless like 304 or 316) is another interesting option. It is essentially a Fe–Cr–Ni alloy. Its conductivity is an order of magnitude lower than Cu (e.g. 304 SS ~14 µΩ·cm, ~12% IACS; some stainless grades go up to ~25% IACS if highly alloyed with Cu, but generally 2–10% IACS is typical) [7]. This high resistivity means that for a given thickness, stainless will produce more ohmic drop. To compensate, stainless collectors might be made thinner or in mesh form. Indeed, research has shown **stainless steel mesh collectors** can perform adequately by allowing the active material to envelope the strands, shortening the electron paths [29]. Stainless has a few major advantages: (i) **It is extremely robust and can be made very thin.** Rolling stainless to <10 µm is feasible (some suppliers offer 5 µm). Additionally, electrodeposition or chemical vapor deposition can produce even sub-micron stainless films (though not at scale). Having a foil half the thickness of Cu partially offsets the conductivity issue, and reduces weight. Neware’s technical article notes that “stainless steel can be processed to be thinner than copper, making it cost-effective and suitable for mass production” [5] – implying that achieving ultra-thin Cu below ~5 µm is very challenging, whereas steel can be thinned more due to strength. (ii) **Corrosion resistance:** stainless is called “stainless” for a reason – its passive chromium oxide layer protects it from most forms of chemical attack [5]. In a battery, this means far less concern about oxide growth consuming the metal; the oxide is self-limiting and quite thin. It also means stainless could be paired with high-voltage or unusual electrolytes without dissolving. For example, in some lithium-air batteries, stainless has been used as a current collector because it tolerates the reactive oxygen species better than Cu or Al would. (iii) **No copper deposition issues:** In cells that get overdischarged, Cu can dissolve into electrolyte and plate on the other electrode, causing internal shorts. Steel does not have a analogous dissolution at low potentials (iron will plate Li rather than dissolve under reducing conditions). Thus using steel might avoid certain failure modes (though one could then get iron contamination if it did corrode). Mechanically, stainless foils are **high-tensile** (often >800 MPa). They have low ductility in foil form (elongation a few percent), so they behave more like a spring – they won’t tear easily, but once bent, they tend to spring back (higher yield strength relative to modulus). This can cause poorer contact with a flat electrode unless pressure is maintained. One workaround is to **perforate or use a mesh**: expanded stainless mesh or punched grids can be embedded into electrodes to improve contact and reduce weight [29]. The open structure also reduces the effective resistivity by giving shorter paths through metal. **Use cases:** Stainless has been considered for lithium metal anodes (as a plating substrate) and for structural battery applications where the cell casing or frame doubles as the current collector. Also, its excellent high-temperature performance could be leveraged in batteries that see heat (like some lithium-ion capacitors that might be soldered onto boards). Cost-wise, stainless steel is relatively cheap per kg (mostly iron), but refining it to foil is more niche (mostly done for specialty electronic applications), so availability in battery-grade coils might be limited.

Iron–Nickel (Fe–Ni) Alloys: This subgroup includes materials like **Invar (Fe~64%, Ni~36%)** and **Alloy 42 (Fe~58%, Ni~42%)** which are known for controlled thermal expansion. Invar's CTE is ~1.3 ppm/K (near zero) (51) , which could be extremely useful to match a ceramic solid electrolyte (which often has CTE ~1–5 ppm/K) – it would minimize thermal stress at the NSS–SES interface. However, Invar's trade-offs are severe: resistivity ~80 μΩ·cm (52) (only ~2% IACS), and it's also quite dense (~8.1 g/cc). That means an Invar foil would be heavy and produce a lot of internal resistance unless very thin or used over small areas. Still, in a scenario where a solid-state battery is cycled across a wide temperature range, a Cu collector's expansion could crack the ceramic electrolyte, whereas an Invar collector would not. If current densities are modest (or supplemental conductive pathways exist), Invar or similar could be justified. Another Fe–Ni material, **nickel-plated steel**, has been used traditionally in cylindrical cell design (for the can or for some tabs). A thin steel foil with a Ni coat could serve as a collector with improved conductivity from the Ni layer and corrosion resistance from both Ni and the stainless substrate. Patents from early 2000s describe Ni-coated steel as a collector to reduce cost relative to pure Ni (53) . This composite essentially behaves similar to stainless or Ni foil in practice.

In summary, **metallic collectors** offer a spectrum: from Cu at the conductive end, through Al, Ni, down to steels at the resistive but strong end. They are all electronically conductive enough for many battery designs (even stainless can work if designed properly), but the choice will depend on whether **electrical performance** (favor Cu, Al) or **mechanical/chemical resilience** (favor Ni, steel) is the priority. Table 1 and Appendix Table A1 compile the quantitative differences.

3.2 Carbon-Based Collectors (Carbon Papers, Cloths, Foams)

Carbon-based current collectors refer to structures made primarily of conductive carbon, such as **carbon fiber papers (felt)**, **woven carbon cloth**, **carbon nanotube (CNT) sheets**, or graphene-based foils. Unlike metals, these are typically porous and flexible. They are essentially **inert in typical battery environments** – carbon does not corrode like a metal does, and it doesn't alloy with lithium (graphitic carbon will intercalate lithium, but a current collector carbon is usually mostly inert fibers with no lithium stored in them). The big compromise is **electrical conductivity**. Carbon fibers themselves can have high conductivity along their length (graphitized fibers can reach 10^5–10^6 S/m) (54) , but when made into a paper or cloth, the contact between fibers and the random orientation reduce bulk conductivity to the range of 10^3–10^4 S/m (30) . For example, a typical carbon paper used in fuel cells has in-plane resistance perhaps 0.1–1 Ω per square for a 200 μm thickness – far higher than a metal foil of even 10× less thickness. Some carbon cloths are improved by weaving and embedding metal strands or by coating fibers with metals or conductive fillers, blurring the line into composites.

Carbon Fiber Paper: Often made by taking PAN-based carbon fibers (5–10 μm diameter each) and forming a non-woven mat that is then carbonized. These papers (e.g. Toray carbon paper used in flow batteries) have void space ~70–80% and are ~100–400 μm thick. Their areal weight is low, and flexibility decent (they can bend, but repeated folding will break fibers eventually). In batteries, carbon papers have been researched as anodes for Li-ion (with Sn or Si deposited on them) (55) or as 3D current collectors for Li metal to plate into. The advantage is **maintaining electronic contact even if the deposited material expands**: the porous carbon network can accommodate expansion better than a flat metal foil (55) . One study found that a tin anode on carbon paper had improved cycling because the paper preserved electrical connection even as Sn particles pulverized, something a planar foil couldn't do [55]. Thus, carbon papers act as both current collector and partial scaffold for active material. However, they usually still need a tab or metallic foil for external connection, since you can't easily weld a carbon paper to the cell terminals. Often a piece of metal is pressed or adhesively attached to serve as a current lead.

Carbon Cloth: Woven from carbon fiber yarn, it tends to be more durable than paper (woven structure gives it tear resistance). Electrical pathways are a bit more defined along the weave. These have seen use in experimental "all-carbon" batteries and in structural batteries (where carbon fiber doubles as both mechanical reinforcement and electrode) [56]. For example, in a "structural battery composite," carbon fiber tow can act as negative electrode and current collector simultaneously [56]. The **energy density is lower**, but it saves weight by multi-functionality. Carbon cloth collectors have excellent flexibility (they can drape over curved surfaces), which metals of equivalent thickness cannot do without fatigue.

Conductive Polymer Films: While not carbon per se, some efforts use polymers loaded with conductive particles as current collectors (e.g. a polymer infused with carbon black or graphene). These are essentially very resistive compared to metals (perhaps 10^2–10^4 S/m), but they offer complete corrosion immunity and can be extremely thin and light. Neware's article mentioned "conductive resins" with graphite and carbon black fillers as a type of composite current collector [57]. These are mostly in R&D; one might envision a thin plastic foil that carries current a short distance to a more conductive bus.

Pros of Carbon Collectors: No metal means no risk of metal corrosion or dendrite-induced short via metal penetration. They are also **thermally lightweight** – low heat capacity and in some cases better heat tolerance than polymers (carbon fibers can handle >400 °C in inert atmospheres easily, though any binder would char). They also do not contribute to cell-level self-discharge via metal contaminants, and they can potentially reduce cell weight (carbon has high strength-to-weight). For instance, carbon fiber has ~ten times higher specific tensile strength than steel. Some studies show **carbon fiber current collectors can improve cell energy density** when used as both electrode and load-bearing component [12].

Cons: The big con is high internal resistance unless augmented with metal. This limits carbon collectors to either **small-area cells** (where absolute resistance is small) or **low-rate applications**. In a high-power cell, a carbon collector would waste a lot of energy as heat. Additionally, contact resistance at fiber-fiber junctions can increase over cycling if the fibers move or if SEI builds up at contacts. Carbon surfaces can also react with electrolyte to form SEI (especially at potentials below 1 V vs Li). While this is not "corrosion" in the metal sense, it can slightly insulate the fibers. Graphitized carbons form a relatively stable SEI though, and some carbon papers are pre-treated to minimize this.

Use Cases: Carbon collectors are found in prototypical **flexible batteries**, where the entire cell can be bent – metal foils would fatigue, but carbon cloth can survive. They are also considered in **solid-state batteries** where a porous carbon current collector could double as host for Li metal or serve as a mixed ionic-electronic conductive scaffold. Another promising area is **structural batteries** (used in aerospace), where carbon fiber layers serve dual roles (carry mechanical load and electrical current) [56]. In such designs, the "current collector" might literally be a carbon fiber laminate that is also part of the device casing or structure.

To summarize, carbon-based collectors prioritize mechanical flexibility and chemical inertness at the cost of conductivity. They often appear in conjunction with metal collectors (e.g. a metal foil current tab attached to a carbon sheet that is embedded in the electrode). In terms of manufacturing, they can be more challenging to handle (fluffy or fraying edges, particulate shedding). But they do not require dry-room handling for oxidation concerns as Cu foils do.

3.3 Metal–Polymer Laminates & Composite Collectors

Composite current collectors attempt to capture the best of both worlds by combining materials – for example, a thin metal layer for conductivity with a polymer backing for strength or safety. There are a few notable concepts:

- **Metal foil on polymer film:** This is akin to flexible printed circuit technology. A copper layer (perhaps 5–10 µm) is laminated onto a polyimide (PI) or polyethylene terephthalate (PET) film of 10–25 µm. The polymer provides mechanical support and insulation, while the copper carries current. In a battery, using such a laminate for the negative collector could provide built-in insulation between cells (useful in bipolar stacking) and prevent burrs from penetrating (the polymer encapsulates the metal edges). It also reduces the metal content (weight) slightly, since polymer is lighter (though thicker). However, a big consideration is **joining**: you cannot weld a polymer-backed foil directly, as the polymer will melt – special techniques (laser that vaporizes polymer then welds metal, or adhesive joining) are needed. These have seen limited use in commercial cells but are explored in advanced concepts and by automotive companies for safer, thinner collectors. For example, Toyota has patents on laminating polyimide to current collectors to act as a shutdown separator and support in case of thermal events [58].

- **Clad metal foils (bi-metal laminates):** A thin laminate of two metals, such as Cu and Al. SCHLENK's mentioned **Al–Cu clad foil** for bipolar electrodes [13] – a single foil that is Cu on one side (to weld to the negative tab/external circuit) and Al on the other (to weld to the positive side of an adjacent cell in a bipolar stack). Such clads are made by roll bonding. In the context of negative-side stability, a clad could be used to put a corrosion-resistant layer on a strong substrate. For instance, Ni-clad stainless steel: stainless for strength, Ni surface for better conductivity and weldability. Or an ultra-thin stainless core with Cu surfaces to reduce overall expansion (the steel core could lower CTE). These are complex to produce but can solve multi-objective problems.

- **Conductive coatings on fiber or fabric:** e.g. metallizing a polymer fabric. A polymer mesh sputter-coated with metal could act as a light collector. But pure polymer without any conductive filler generally isn't used alone due to conductivity limits.

Composite collectors are often **tailored for specific design objectives**: e.g., a safety-focused cell might use a metal-polymer laminate that stops propagation of internal shorts (the polymer layer could act as a built-in shutdown layer if overheated). Another scenario is a **flexible battery cable or harness** where current collectors double as flex connectors – then a polymer-backed Cu foil is essentially what a flex cable is, and indeed one can imagine a cell wherein collectors extend out as flexible tabs (polymer backed to prevent shorts).

In terms of performance: a polymer backing adds thickness (which slightly increases the distance ions/electrons must travel if the polymer is between electrode and collector – usually it's behind the metal, so not in the electron path, but it might block heat flow). It also limits operating temperature (most polymers in batteries can't go above 120 °C safely). If a cell incurs a short, a polymer may melt or shrink – sometimes good (can shut off current) or bad (can deform cell geometry). So engineering these requires careful choice of polymer (high-temp polymers like Kapton®, or flame-retardant ones).

Manufacturability can be an issue as well: laminating foil to film without trapping bubbles or causing curl is non-trivial. The layers may have different CTEs causing curl. Additionally, slitting a laminate can still produce burrs on the metal edge or delamination if not done properly.

Overall, composite collectors remain an emerging solution for special cases, rather than a widespread standard. They illustrate the attempts to overcome limitations of single materials by hybridizing.

3.4 Coated & Surface-Treated Foils

This category is not a separate substrate material, but rather common enhancements applied to the above collectors. Because surface properties of the collector are crucial for interface stability, a variety of **coatings and treatments** are used:

- **Carbon Coatings on Metals:** As noted earlier, carbon-coated aluminum or copper foils are popular in lithium-ion industry to reduce interface resistance and improve electrode adhesion (59) (60). A thin layer (~3–5 µm) of conductive carbon (often graphite or carbon black in a polymer binder) is coated onto the foil. This has multiple effects: it **physically separates the active material from the native oxide layer of the metal**, thus avoiding the insulating effect of, say, Al_2O_3 ㉝. It also provides a more textured, high-surface area contact that can distribute current more evenly. For example, a LiFePO_4 cathode on carbon-coated Al had much better high-rate performance than on bare Al (61) ⑨. Specifically, Striebel et al. reported the **contact resistance dropped from ~200 to ~40 $\Omega \cdot cm^2$** with carbon coating on Al ⑨. Similarly, Wu et al. found carbon-coated Cu improved both electronic and ionic interface properties for a Li_4Ti_5O_12 anode (62). Carbon coatings can be applied by slot-die coating a carbon slurry or by chemical vapor deposition (CVD) to grow a pyrolytic carbon layer. There are also advanced carbon interlayers like vertically aligned carbon nanotubes or graphene that act almost like tiny springs or wires between collector and electrode (63) ②. These can accommodate volume changes and maintain contact.

- **Metal Platings and Thin Films:** Coating the collector with a different metal can impart new properties. For negative collectors, **lithiophilic metals** – ones that have a low nucleation overpotential for lithium – are especially of interest. Examples: **Sn (tin)**, **Ag (silver)**, **Au (gold)** coatings on Cu. Tin is relatively cheap and has been studied as an interfacial layer that alloys slightly with initial lithium plating to form LixSn, which is believed to promote uniform lithium deposition (less dendritic growth) ⑩. It also serves as a **barrier to prevent direct Cu–Li contact**, since Cu can catalyze dendrites. Ag and Au don't alloy with Li but provide excellent conductivity and wettability for Li (Li melts wet gold and silver surfaces). A study cited in a review notes that while these metal coatings help performance, their **high cost and added mass** are drawbacks ⑭. Typically, a few hundred nm of these metals is enough, which is a small mass addition but cost for Au is huge. Some commercial lithium metal pouch cells reportedly use a thin Ni or Ag plating on Cu to improve cycling (Ni to prevent Cu diffusion perhaps, Ag to aid Li spreading).

Other metallic coatings could aim at corrosion resistance: e.g. a thin **nickel plating on copper** can stop copper from dissolving in certain electrolytes (Ni forms a protective layer). In fact, nickel-plated copper foil is used in some cases where electrolyte additives might corrode plain copper. Another interesting one is **zincate treatment** for Al – historically, Al current collectors are zincated (a dip that replaces surface Al_2O_3 with a thin Zn layer) before applying certain coatings.

- **Oxide/Ceramic Coatings:** Atomic layer deposition (ALD) and related techniques allow a conformal ultra-thin oxide or ceramic film on collectors. For instance, ALD **Al_2O_3 on copper** has been studied as a way to protect Cu from corrosion and possibly to regulate lithium plating behavior. MDPI "Materials" 2019 paper reported ALD Al_2O_3/TiO_2 films can increase polarization resistance of Cu in aqueous electrolyte by ~100× (from order 10^5 to 10^7 $\Omega \cdot cm^2$) (64) (65). In batteries, Peng et al. (ref. in literature) showed that a ~5 nm ALD Al_2O_3 on Cu suppressed the growth of Cu dendrites in a LiPF_6 electrolyte by blocking direct contact with electrolyte, without severely impacting conductivity because the layer is so thin (and likely breaks down slightly to allow electron tunneling). One must note, an insulating coating like pure Al_2O_3 needs to be either extremely thin or intentionally slightly porous so that it doesn't completely prevent electron transfer. Often these coatings function by initially serving as a barrier, then during cell formation they might acquire Li (becoming Li–Al–O compounds) that conduct Li^+ or they fracture microscopically to still allow electron percolation. Another approach is using **lithiated compounds** as coatings – e.g. LiPON or LiF or LiNxOy on Cu to help form a stable artificial SEI. Some patents describe Li-rich coatings on Cu to immediately consume any reaction that would otherwise involve the Cu directly [66].

- **Surface Texturing:** Not a "coating" added, but a treatment – for example, **electrochemical roughening** of Cu to create a dense array of microscopic peaks (common in PCB foils) can improve the mechanical anchoring of electrode material. In the IZ context, a rougher foil has more true contact area with a composite electrode, lowering contact resistance. However, it also means higher surface area that could foster side reactions if directly exposed to electrolyte. So sometimes a combo is used: roughen the foil, then coat with carbon to fill in the asperities and protect the fresh surface [67] [61]. For stainless steel, surface etching or oxidation can improve adhesion (e.g. a slight oxide might help bind a polymer electrolyte).

- **Wetting layers for Solid-State:** In solid-state batteries, one challenge is making the lithium (whether plating or a pressed foil) wet the current collector uniformly. Here, coatings like a thin **Indium** layer have been explored – Indium is very lithiophilic and can form a liquid alloy with Li at moderate temperature, which then spreads and ensures contact. Similarly, gold coating on stainless or nickel can improve interfacial contact with solid Li or Na metal by avoiding oxide formation at the interface.

Overall, coated and treated foils aim to enhance **interface zone stability** without changing the bulk collector. They are increasingly standard: e.g., **commercial carbon-coated foils** are offered by many suppliers and are used in EV-grade batteries for both anodes and cathodes [68] [69]. The proper coating can significantly extend cycle life; for instance, a carbon undercoat on Al foil was shown to improve a LiNiCoAlO_2 cathode's capacity retention over hundreds of cycles by preventing Al corrosion and maintaining good contact [70] [71]. On the anode side, carbon-coated Cu has been reported to reduce initial interface impedance and improve first-cycle efficiency by limiting the direct exposure of Cu to electrolyte (which can scavenge Li to form CuLi if the potential goes slightly below 0 V, although minor) [72].

From a **manufacturing standpoint**, adding coatings is an extra step (cost), but often worth it. It can be done in-line (some foil makers produce carbon-coated foil directly in their process). ALD or PVD coatings are done in batches and are costlier, thus mostly seen in research or high-value products (e.g. military batteries or solid-state prototypes). The thickness and uniformity control is crucial – a patchy coating could create non-uniform current distribution (leading to hot spots or dendrites).

In conclusion for collector families: the base material provides the fundamental electrical and mechanical backbone, while coatings/interlayers fine-tune the surface chemistry and micro-contact mechanics of the interface zone. The best performance often comes from the right combination (e.g. a high-conductivity foil plus a tailored coating addressing its weaknesses).

4. Interlayers & Surface Engineering

Building on the coated foils discussion, we examine **interlayers and surface-engineering strategies** in a more generalized way. These are "functional layers" introduced at the NSS–SES interface to improve stability. They can be applied onto the collector, onto the electrode, or in between as a discrete layer. We focus here on those associated with the negative collector side. Key functions of interlayers include:

- **Barrier Function:** Preventing detrimental direct contact between two reactive components. Example: a thin polymer or oxide layer on Cu that prevents corrosive species or lithium from directly attacking the Cu. As noted, ALD Al_2O_3 is a barrier that stops copper from corroding in electrolyte [64]. In solid-state cells, a metal fluoride or nitride layer (e.g. LiF, Li_3N) might be applied on Li or Cu to prevent interdiffusion or reactions at the interface.

- **Wetting & Lithiophilicity:** Promoting uniform deposition or adhesion of lithium (or other active material) on the collector. Metallic interlayers like Sn, Zn, Ag, Au serve this purpose. They have been shown to reduce nucleation overpotential for lithium plating [14], leading to smoother lithium layers. For instance, a tin-coated Cu will form Cu_6Sn_5 and then Li_xSn at the interface, which presents a lower energy surface for Li to plate on, thus spreading the Li more evenly (suppressing dendritic growth) [10]. Carbon coatings can also aid wettability by providing a porous conduit for Li-ions, somewhat like a sponge that distributes incoming Li.

- **Contact Leveling & Compliance:** Ensuring intimate contact across the interface, even if surfaces are rough or undergoing expansion/contraction. A soft or porous interlayer can take up space changes. **Carbon nanotube (CNT) carpets** are an example – a CNT coating on a foil creates a tiny springy gap-filler between the foil and the electrode coating [63]. When the electrode expands, the CNTs compress; when it contracts, they stretch – maintaining contact and conductivity. Similarly, a polymer layer (e.g. a conductive polymer or a gel) might be placed to keep two hard surfaces (like Cu foil and ceramic electrolyte) in contact without gaps. In one study, an "electron-deficient carbon" interlayer (basically a lithiated carbon) was used on Cu to maintain electronic percolation in an anode-free cell, compensating for the insulating nature of the developing SEI [73].

- **SEI Modulation:** Although the solid-electrolyte interphase (SEI) is typically a result of electrolyte decomposition on the anode material, in cases of anode-free cells, the SEI initially forms on the current collector. Interlayers can be designed to modify SEI composition – e.g. a layer rich in F^- could ensure LiF-rich SEI (which is more stable). Some researchers have used LiF or Li-rich additives coated on Cu to pre-form a favorable interphase before lithium deposition. These can be considered part of interface engineering.

- **Adhesion Promotion:** For composite electrodes (like a graphite coating on Cu foil), an interlayer can improve adhesion between the active mass and the foil. A classic example is a polymer binder layer or a silane coupling agent applied to the foil. Carbon coatings also improve adhesion by giving the foil a rough, high-surface area face for the binder to grab onto [67]. Good adhesion prevents delamination during cycling. If an anode coating delaminates even partially, that area loses electrical contact, leading to accelerated degradation (and effectively creating a "hot spot" current-wise, since other areas carry more current).

Concrete examples of interlayer implementations:

- **"Artificial SEI" coatings:** e.g. a thin layer of Li_3PO_4 or LiNbO_3 deposited on a Li-metal or Cu surface. These are ionically conductive but electronically insulating, so they can block electrondriven side reactions while allowing Li^+ to pass. By applying such a layer, the idea is to prevent the continuous growth of a resistive SEI or dendrites – it's a predetermined, stable interface. However, if applied on Cu (with no Li initially), one must consider how Li ions will get through during first plating – typically these layers are so thin (tens of nm) that Li can tunnel or migrate through easily once ionic percolation paths form.

- **Graphene and 2D coatings:** Graphene is a great conductor and chemically inert. A single or few-layer graphene film on copper has been shown to reduce corrosion and also act as a diffusion barrier [63]. One might coat Cu with graphene via CVD; that graphene protects the Cu from reacting with electrolyte and also provides a high surface area interface (if slightly defective or porous, it can still transmit Li ions). "Carbon nanowalls" (vertical graphene sheets) have been demonstrated to improve both electrical and thermal performance of collectors [74] – they basically turn the surface into a high-surface-area brush that can take up lithium or bind electrode particles strongly.

- **Polymer buffer layers:** A thin (~1 µm) layer of a polymer like PVDF or a rubbery electrolyte can buffer stress. For instance, a proprietary approach from Blue Solutions (a solid-state battery maker) involved a polymer-coated foil that improved contact with their polymer electrolyte. The polymer had mixed ionic-electronic conductivity. By adjusting the modulus of that polymer, they could reduce pressure required to maintain contact. In another approach, a water-based polyimide primer on Cu was found to increase graphite coating adhesion drastically, without adding much resistance (since the polyimide was very thin and partially conductive due to carbon additives).

It is important that any interlayer **not introduce an undesired interface of its own**. Each added layer is another interface (e.g. collector/coating and coating/electrode). So ideally it should bond strongly to both sides. Many surface treatments, like silanes, create covalent bonds between metal oxide and binder, effectively "gluing" them. Carbon coatings create a mechanical interlock. In some cases, a multilayer coating is used: for example, a Cu foil might first be nickel-plated (for adherence), then carbon-coated – the Ni helps the carbon stick to Cu (as carbon has poor adhesion on smooth Cu directly). These engineering nuances are beyond scope to detail fully, but they highlight that surface engineering is a complex field.

From a **regulatory and safety perspective**, introducing interlayer materials means they must be compatible with the cell chemistry long-term (not decompose into harmful byproducts). For instance, any polymer used must not catalyze lithium dendrites or react to form gases. In solid-state systems, inorganic interlayers must match thermal expansion to avoid cracking when the cell is cooled or heated.

Finally, interlayers often come into play during cell **manufacturing**: a coating on foil might alter wetting of slurry, for example. Carbon-coated foils can sometimes make it harder for aqueous electrode slurries to coat (since they are hydrophobic) [50], so adjustments in formulation are needed. Some manufacturers skip carbon coating on the very edge of foils to maintain good welding areas (since carbon can interfere with ultrasonic weld quality). These are practical considerations linking back to "manufacturability" of the interface design.

In summary, interlayers are essential tools to achieve interface zone stability, especially as battery chemistries push limits (high capacity, no excess lithium, solid electrolytes, etc.). The guiding principle is to use the minimal layer needed to address the specific failure mode anticipated – be it a mechanical buffer, a protective barrier, or a seeding layer for uniform lithium growth. The Appendix provides a quick reference table (Table A2) of common interlayer types and their roles.

5. Edge Integrity & Center Hot-Spots

Mechanical stability of the collector and its coating is not just a bulk property – **edge and surface defects** can dominate failure modes in the interface zone. Two particular issues are (a) edge-originating problems, like burrs or delamination at the foil edges, and (b) non-uniformities across the area, leading to localized hot-spots (areas of higher resistance or current density).

Edge Burrs & Slitting Quality: During electrode manufacturing, large foils are slit into narrow rolls for winding or are cut into sheets for stacking. If the cutting tooling is dull or misaligned, it can create **burrs – tiny metal protrusions or rough edges** on the foil [75] [76]. In a finished cell, these burrs can pierce through separators or solid electrolytes, directly shorting the negative and positive electrodes [76]. They are a well-documented safety hazard: a burr-caused internal short can lead to localized heating and potentially thermal runaway [77] [78]. Even if no immediate short, burrs can initiate lithium plating sites (sharp points concentrate electric field, encouraging dendrite growth towards the opposite electrode). Therefore, controlling edge quality is paramount.

Modern factories employ **vision systems and microscopes for burr detection** on electrode sheets [77]. According to Leica Microsystems' 2024 report, optical inspection at strategic process steps can reliably spot burrs as small as a few microns and assess their "damage potential" [78] [77]. Their microscopy image (Figure 1 in the Leica whitepaper) shows red arrows pointing to burrs at an electrode edge [79]. The authors note burrs are usually introduced at slitting or sometimes at ultrasonic welding of tabs [80]. They recommend at-line inspection and have a classification for burr severity. Minor burrs might just cause self-discharge (by connecting to the other electrode through electrolyte causing a micro-short), whereas major ones can penetrate separator immediately [77].

Mitigation of Burrs: Sharp tooling and proper maintenance is the primary prevention. **Laser cutting** is emerging as an alternative to mechanical slitting for electrodes; ultrafast lasers can cut foil and coated electrode with almost no burr and a heat-affected zone of only ~10 µm [81]. LaserFocusWorld reported that UV or ultrafast IR lasers produce **smooth, burr-free edges** on foils, reducing defects and improving downstream winding [81]. Some cell designs also **insulate edges** of collectors deliberately – for example, by edge-coating with an insulator or by using slightly narrower collector foils than the coating (so active material overlaps the edge, encapsulating it in binder). This way, any burr that might exist is at least covered by a layer of non-conductive material, preventing direct contact with opposite electrode. In solid-state cells, edge burrs can still crack a ceramic electrolyte on stacking, so mechanical smoothing (like calendering the edges, or using a deburring tape) is done. For instance, electrodes may be fed through a **brush or anvil after slitting** to break off any weak burrs.

Foil Edge Coatings & Corrosion: Another edge consideration – many foil coatings (like carbon) are not applied all the way to the very edge of the foil, because that edge is needed for welding tabs and also because coatings can flake at edges. If the bare metal edge is exposed and if any moisture ingresses, corrosion tends to start at edges (higher exposed surface area). This is more a long-term durability issue. In high-quality cells, they often implement a "tab seal tape" or edge tape in the jellyroll to cover the edges of the negative foils, minimizing electrolyte access there.

Center Hot-Spots (Non-Uniform Contact): Even if edges are perfect, the center area of the electrode stack can develop problems if there's **non-uniform pressure or contact**. One scenario: if a negative electrode coating has spots of poor adhesion to the foil (voids or bubbles at the interface), those spots will have higher local impedance. During charge/discharge, current will avoid those spots and concentrate in nearby well-adhered regions, which then carry higher current density – potentially overheating (a "hot spot"). Over time this can cause accelerated degradation or local lithium plating in those high-current zones. Detecting such interface voids is challenging. Researchers have used methods like ultrasonic scanning or X-ray tomography to identify **partial delamination** areas. For instance, X-ray radiography can see slight differences in coating thickness that indicate a lift-off [82] . Inline, this is hard to do on every piece, but sampling is done.

Another contributor to hot-spots is **non-uniform stack pressure** in larger format cells. If the cell stack or jellyroll isn't perfectly flat, some central regions might not be pressed as firmly against the separator or collector, increasing local resistance. When current flows, those regions heat a bit more (I^2R losses), which could then further degrade the interface there (creating a feedback loop of rising impedance). Thermal imaging can catch this in prototype cells – one might see a slightly warmer patch in the cell center during high discharge. The remedy is usually to improve cell assembly flatness and apply sufficient compression (in module design, a foam or spring element can even out the pressure).

Edge vs. Center failure patterns: It's observed that many cell failures initiate at edges (due to burrs, tab weld issues, or faster electrolyte degradation at edges where exposure is higher). However, center failures happen too, especially related to **center current collector breakage** in large pouch cells. During charge, the cell swells; if the collector foil is not compliant enough, it could strain and eventually crack in the middle where bending is maximum. Once a foil cracks in the interior, that area goes "dead" (loses conduction), leading to a hotspot around the crack due to current re-routing through remaining metal. This is one reason alloy foils (with higher elongation or strength) are considered – to avoid such internal fracture under repeated strain.

Metrology & QC for Interface Contact: To ensure bonding quality of electrode to collector, manufacturers conduct **peel tests** (to measure adhesion force). While that's not inline, it's a routine QA test. For inline, a novel approach is being researched: **electrochemical impedance spectroscopy (EIS) mapping** of electrodes before cell assembly. One can place a sheet of electrode in a fixture with a reference electrode and scan the impedance at various points. If a spot has high interface impedance, it shows up as an anomalous point in the map. Another method is **eddy current testing** – passing an AC coil over the foil can detect if the foil has uniform conductivity or if any cracks/voids exist (a crack changes the eddy current flow, similarly a well-adhered vs not coating might change local conductivity slightly). Eddy current sensors are used in some pilot lines for detecting foil defects like hidden cracks or thickness deviations.

Leica's paper and others emphasize **multi-scale inspection**: macro (camera for big defects), micro (microscope or ultrasonic for small voids), and testing a finished cell via non-destructive means (like CT scan or thermal imaging on first few cycles). For instance, micro-CT can visualize delamination and voids at the interface with ~1 µm resolution, albeit not inline due to time.

Inline Impedance Monitoring: The idea alluded to in the prompt ("inline impedance prospects") is likely about embedding sensors or using the collector itself as a sensor. Some experimental cells have used the current collector as a distributed sense line – by applying a high-frequency signal along the collector and measuring reflections or impedance, they can tell if there's a non-uniform contact (similar to TDR – time-domain reflectometry – used in wires). While not commercial yet, it's a prospect for smart battery monitoring.

Tab and Weld Concentration: Although more of a design aspect, note that current collectors near the tab (welding point) see higher current density – sometimes coatings are removed near tabs to ensure low-resistance metal-to-metal welds. But that means near the tab there is a region of bare foil which might corrode or have different SEI. Proper design often includes a **tab slurry step-down** – active material is tapered off near the tab to avoid too abrupt a current crowding. Otherwise the tab region can overheat (a hot spot at edge).

In summary, maintaining **edge integrity** (burr-free, well-protected edges) and **uniform interface contact across the area** (no delamination or slack) is critical to achieving the longevity and safety promised by advanced collectors. The best collector material can be undermined by a tiny burr or a small void, so process control and inspection are as important as material choice.

6. Selection Playbook

Choosing the optimal negative-side collector (and any interlayers) requires balancing the criteria for a given application scenario. Below is a “playbook” with a few common scenarios and recommended selections, along with rationale:

- **High-Power or Fast-Charging Cells (e.g. EV batteries requiring high C-rate):** Priority: lowest possible electrical resistance and robust cycling at high current. Recommendation: Use high-conductivity metal collectors (Cu is default; Al only if anode potential allows). Ensure collector thickness is sufficient to avoid excessive voltage drop (e.g. 10 µm Cu rather than 6 µm if very high currents are expected, to reduce sheet resistance). Avoid high-resistivity options like stainless or pure carbon here. Apply a carbon coating or conductive primer on the collector to minimize interface contact resistance (especially important at high C-rates, where a 5x lower contact resistance can markedly reduce heat generation [9]). Also consider high-tensile Cu if using a silicon or expansive anode, so that foil maintains contact under fast expansion/contraction. Verify edge smoothness to prevent localized current hot-spots (a burr could get much hotter under fast charge). For cooling, note that Cu’s high thermal conductivity aids in spreading heat – another reason to stick to metals. **Example:** A high-power graphite/NMC cell – 10 µm Cu foil, double-sided carbon coated for interface, with carefully slit edges and ultrasonic welded tabs, is a tried-and-true configuration [68] [72].

- **Thick Electrode / High-Energy Cells (e.g. for maximizing energy density, slow-rate):** Priority: weight saving and accommodating large expansions (if any), over absolute conductivity. Recommendation: Here one might push towards thinner or lighter collectors. For instance, using 6 µm Cu instead of 10 µm to gain energy density – but only if the discharge rates are low to moderate (to tolerate the higher resistance of thinner Cu and risk of foil tear during calendering of thick coatings). If the cell chemistry allows, consider aluminum for further weight saving – e.g. in a lithium titanate (LTO) anode cell, Al foil can replace Cu since LTO anode sits at ~1.55 V (Li), eliminating Li-alloy risk [25]. Al would cut collector weight by ~70%. If using Al, a thin carbon or nickel coating on it would be wise to handle its oxide and improve conductivity at the interface [33]. For very thick silicon composite anodes that only discharge slowly, a high-tensile Cu or even a Cu-coated polymer mesh could be employed to allow expansion. The focus is ensuring the foil doesn’t become the bottleneck: you can tolerate some resistive loss if discharge is slow, but you cannot tolerate the foil breaking or the interface separating. So mechanical reinforcement via alloyed foil or polymer support can help. **Example:** A stationary storage cell aiming for max Wh/kg – might use a 5 µm Cu on 5 µm polyimide laminate as the anode collector, halving weight vs standard 10 µm Cu, since high power isn’t needed. The polyimide gives it enough strength to handle thick coatings. However, one must then carefully heat-manage because a thinner collector dissipates heat less effectively.

- **Extreme Cyclability / Long-Life Cells (e.g. >10,000 cycles, as in grid storage or certain EVs):** Priority: interface stability over time, corrosion resistance. Recommendation: Favor materials that resist gradual degradation – Ni or stainless steel could be attractive despite higher initial resistance, if the cell operates at low enough rates. For instance, a lithium-ion capacitor or a long-life industrial battery might use a stainless steel current collector to virtually eliminate collector corrosion as a failure mode. If using Cu or Al, surface engineering is vital: carbon coat to prevent oxide buildup, or a protective metal coat (like Ni-plating on Cu to guard against copper dissolution into electrolyte over years). Also consider using slightly thicker foil than minimum, to avoid gradual growth of resistance if some corrosion or spiral cracking occurs. In high-cycle applications, **collector fatigue** can occur (repeated expansion/contraction might cause microscopic cracks in foil or at the foil-coating interface). High-strength foils or those with ductile coatings (CNTs, etc.) can alleviate that. **Example:** a 48 V mild-hybrid battery targeting 15-year life – one could use a nickel-plated Cu foil for the anode: Cu for conductivity initially, Ni surface to ensure no copper dissolves into electrolyte over time (some long-term studies show trace Cu can migrate into the SEI and catalyze loss; Ni barrier stops that) [83] . The Ni also self-passivates, so if any moisture enters over life, the NiO forms and halts further attack.

- **Lithium-Metal or Anode-Free Cells:** Priority: uniform lithium plating/stripping and preventing short circuits (dendrites). Recommendation: Use a lithiophilic coated collector. Copper foil is a base choice (common in coin cell tests), but unmodified Cu can lead to non-uniform Li nucleation and early shorting. Instead, a thin layer of lithiophilic metal (Sn, Ag, Zn, etc.) on Cu is recommended to guide smooth Li deposition [10] . Alternatively, a 3D structured collector like a Cu or Ni foam, or a carbon scaffold, can be used to host the plated Li and reduce effective current density. If using a solid-state electrolyte, consider a stack pressure – here a **springy interlayer** (e.g. CNTs on Cu) can maintain contact as Li is plated and stripped, preventing gaps. Nickel foil is also a candidate because it doesn’t alloy with Li and has a higher hardness which might suppress dendrite penetration. Some solid-state designs use a **stainless steel foil current collector for Li metal** to benefit from its strength and lack of reactivity – the higher resistivity is mitigated by the fact that Li metal itself becomes the conductor once plated. Always ensure edges of the collector in anode-free designs are well insulated or recessed – lithium can plate around edges leading to shorts if not. **Example:** an anode-free pouch cell (Cu foil initially bare) – treat the Cu with a dual coating: ~50 nm of Ti to improve adhesion, then ~100 nm of lithium-indium alloy sputtered (Indium for lithiophilicity). During first charge, Li plates on this Li-In wettable surface forming a smooth layer. The Ti prevents the coating from peeling off Cu. This kind of engineered interface can dramatically improve Coulombic efficiency of first plating and delay short-circuiting.

- **Solid-State Battery with Brittle Electrolyte (e.g. ceramic):** Priority: CTE match and constant contact under stress. Recommendation: Consider low CTE alloy collectors (like Invar or controlled expansion clads) if thermal excursions are expected, to avoid cracking the ceramic at the interface. Also use a **compliant interlayer**: for instance, a thin foil coated with a soft metal (like an Sn or indium) that on assembly forms a thin alloy or eutectic at the interface, filling any microgaps. One approach is a silver-carbon composite layer that can deform to account for surface roughness of the ceramic. Stainless steel could be a good collector here since many ceramics (LLZO etc.) have CTE ~10 ppm/K and 304 steel ~17 ppm/K – closer than Cu’s 16 vs maybe not huge difference with Cu, but Fe–Ni alloys can go as low as ~5 ppm/K which may match some glass ceramics. If the solid electrolyte requires high stack pressure, choose a collector that won’t creep – again stainless or Ni excel in this regard at room temperature (Cu might creep slightly under constant high pressure at moderate temp). Use of **foil vs mesh:** some solid-state stack designs use perforated collectors to allow electrolyte and electrode to “sinter” together through the holes, achieving better physical coupling. For example, a thin expanded Ni mesh embedded in Li metal can make a stable interface to a ceramic by providing mechanical anchoring.

- **Low-Cost or Supply-Constrained Situations:** Priority: cost and material availability over ultimate performance. Recommendation: Use commonly available metals – Cu and Al are widely available; Ni can be pricey. If copper prices are a concern or if cell does not need high rate, one could use a thinner Cu or even look at coated aluminum for the anode (with all the caveats discussed). Some manufacturers have explored copper-clad steel (a thin Cu on a steel foil) to save copper – the steel provides bulk (cheaper), Cu provides surface conductivity. This is heavier though. From a process standpoint, use standard formats that suppliers can easily provide (e.g. 10 µm Cu is easier to get than 5 µm). Also consider recycling: stainless steel current collectors could be attractive as they are easily separable and 100% recyclable (stainless scrap value is decent). If a product doesn't need top performance, even **carbon-coated aluminum** for an anode in a Li-ion (like LTO anode) could cut cost due to Al's cheaper price per tonne vs Cu. In summary, tailor the material choice to the value proposition of the product – e.g. an ultracheap stationary battery might accept slightly worse performance to use aluminum current collectors on both sides for simplicity.

These scenarios highlight how the decision matrix might work. Often, real designs have multiple constraints (e.g. an EV cell needs high power and low cost and long life). Thus the final collector choice is usually a conservative one (Cu foil with small tweaks) unless a specific pain point pushes a new material. When adopting a new family (like stainless or carbon), thorough testing is needed to ensure no hidden interactions (for instance, SS might catalyze electrolyte reduction differently than Cu, so the SEI could differ).

Checklist for Collector Selection: (as a quick reference for engineers)

- Electrical: Does the collector keep ohmic losses < desired threshold at max current? (Calculate sheet resistance * current density * current path length for worst-case.) If not, increase thickness or switch to more conductive metal.
- Mechanical: Will the collector survive manufacturing (slitting, winding, welding) and cycling stresses? (Check tensile strength vs. web tension, elongation vs. expansion of electrode, bending radius vs. winding radius.) If marginal, consider alloy or polymer support.
- Interface Contact: Does the baseline collector surface bond well with the electrode or solid electrolyte? (Consult adhesion tests; if poor, plan for a coating like carbon or use a surface texture.)
- Chemical Stability: Is the collector stable at the operating potential range and with chosen electrolyte? (For liquid cells: Cu ok for 0 V, Al not; for solid: steel ok with sulfide? e.g. watch out for stainless reacting with sulfide electrolytes releasing Ni/Fe – coatings may be needed.)
- Environmental/Processing: Can the collector handle the manufacturing environment (e.g. water-based slurry for electrode)? If using Al with water-based anode slurry, must carbon-coat it [50]. If using steel, ensure no rust (store in low humidity before assembly or use pre-passivated foil).
- Joining: Can you weld/solder the collector to terminals easily? If using an exotic material, you might need ultrasonic welding instead of resistance welding, etc. Also dissimilar metal joining (Cu tab to Ni foil) may need intermediate layers.
- Cost: Is the material readily available in required specs? (Check supplier list – if only one supplier of 5 µm Ni foil, risk in supply; maybe use 8 µm if more common.)

Using this checklist, one can iterate to a suitable choice. In many cases, it circles back to a known solution (there's a reason Cu and Al dominate). But as demands evolve (solid-state, huge cycle life, structural integration), alternatives become more favorable.

7. Appendix

7.1 Definitions and Formulas

- **Resistivity (ρ)**: a material property indicating how strongly it opposes electric current, in units of Ω·cm or more commonly here µΩ·cm (micro-ohm-centimeter). Related to conductivity σ by σ =

1/ρ. For a rectangular foil, resistance R = ρ * (length / cross-sectional area). Often normalized as **sheet resistance (R□)** for a thin film: R□ = ρ / thickness. For example, ρ_Cu ≈ 1.7 µΩ·cm; at thickness t=10 µm (which is 0.001 cm), R□ ≈ 1.7 µΩ·cm / 0.001 cm = 1700 µΩ = 1.7 mΩ per square.

- **% IACS**: percentage of the International Annealed Copper Standard conductivity. 100% IACS is defined as 58 MS/m (which corresponds to ρ = 1.7241 µΩ·cm at 20°C). A material at 50% IACS has twice the resistivity of copper. This metric is common in alloy datasheets (84) .

- **CTE (Coefficient of Thermal Expansion)**: in ppm/K, how much a material expands per degree. Mismatch in CTE between collector and solid electrolyte or electrode can cause stress. e.g. Cu ~16 ppm/K, typical oxide ceramic ~10 ppm/K, thus a 50°C change yields ~0.03% strain differential per degree of separation.

- **Yield Strength vs. Tensile Strength**: Yield (YS) is the stress at which permanent deformation begins (0.2% offset typically); Ultimate Tensile Strength (UTS) is max stress before breaking. Thin metal foils often don't exhibit a traditional yield point – they can be elastic up to a point then break. Reported foil strengths (like "500 MPa") usually refer to UTS from tensile tests ⑲ . In operation, any stress beyond yield could lead to foil necking or cracking over cycles. Using UTS as a comparative metric is fine for our purposes.

- **Bending Radius (min)**: the smallest radius a foil can be bent around without cracking. Often given as a multiple of thickness (R_min ≈ k * t). For RA Cu foil, a rule of thumb is ~6–10× thickness for a 90° bend without fracture (85) . If foil is coated or brittle, radius must be larger.

- **Areal Resistance (Ω·cm^2)**: Used for interfaces – e.g. contact resistance between electrode and collector. It multiplies current density to give a drop (Ω·cm^2 * mA/cm^2 = mV drop). We cited carbon coating reducing contact from 200 to 40 Ω·cm^2 ⑨ ; at 1 mA/cm^2, that's difference of 0.2 Ω·cm^2 *1 = 0.2 V drop vs 0.04 V, a big improvement.

- **Stack Pressure**: the pressure compressing layers in a cell (in kPa or MPa). Solid-state batteries might use 10–50 MPa to keep contact. Foils must not yield or creep under that. Cu will deform plastically at relatively low pressure over time (creep), whereas Ni or steel withstand more. Creep is time-dependent strain under stress; high tensile alloys are designed to reduce creep at given stress/temperature (86) .

- **Dendrite**: filament of Li that can grow during charging. Current collector surfaces/coatings influence dendrite nucleation. Lithiophilic surfaces promote uniform plating (dendrites are less likely if plating is uniform). Measures like critical current density and Sand's time (time to dendrite) are used to evaluate plating behavior with different collectors.

7.2 Data Tables

Table A1 – Material Properties of Negative-Side Collector Families (consolidating typical values from multiple sources)

Family (Material)	Density (g/cc)	Elastic Modulus (GPa)	ρ (µΩ·cm) @20°C	%IACS	CTE (ppm/K)	UTS (MPa) (typical)	Elongation (%)	Notes/Source Refs
Copper (C1100 foil)	8.96 [87]	~110 (RA foil)	1.7 [88]	100%	~16.5	300 (anneal) – 400 (hard) [15]	~5–20 (cond. on temper)	Pure Cu, ED foil can reach ~400 MPa [15]. Oxidizes easily.
Cu High-Tensile Alloy	~8.8 (Cu+X)	~120–130	~2.0 – 4.3	50–86% [19]	~15	500–750 [19]	~1–10	E.g. Cu–0.3%Sn, Cu–Ni. Trade strength vs cond. [19].
Aluminum (1100)	2.70 [4]	70	2.65 [4]	64%	~23	~90 (anneal) – 150 (work)	10–25	Prone to Li alloy <0 V. Instant Al_2O_3 film.
Nickel (Ni 201)	8.9 [87]	~180	6.4 [6]	27%	~13	~600 (hard rolled) [21]	1–10 (hard) / 30 (anneal) [22]	Magnetic. Corrosion-resistant. Electroformed Ni: 780 MPa @10 µm [89].
Stainless (304)	7.9	~200	~72 (range 40–80) [7]	~2–3%	~17	600–1000 (hard)	2–10	Non-magnetic (304). Cr/Ni passive layer. Resistivity varies by alloy (ferritic SS ~70 µΩ·cm).
Fe–Ni (Invar 36)	8.1	140	~82 [42]	~2%	1.3 (at 20°C) [51]	~500	0–1	Very low expansion. Used in special cases; not conductive. Brittle in foil.
Carbon Fiber Paper	~0.5 (bulk, due to porosity)	~20 (in-plane, est.)	– (anisotropic, see note)	–	~0 (fiber), effective ~<5 (with binder)	~30–50 (fiber yield)	0–1 (fiber), paper bulk brittle	In-plane cond. ~10^3–10^4 S/m [30] (equiv ~10^5 µΩ·cm resistivity). Through-plane very high resist.

Family (Material)	Density (g/cc)	Elastic Modulus (GPa)	ρ (μΩ·cm) @20°C	%IACS	CTE (ppm/K)	UTS (MPa) (typical)	Elongation (%)	Notes/Source Refs
Carbon Cloth	~1.3 (solid fiber)	~70 along fiber (fiber intrinsic)	similar to above	–	~0	~250 (fiber break)	~2–3 fiber break	Woven structure improves handling. Typically need metal current take-off.
Cu on PI laminate	1.4 (PI) + Cu	PI ~5; Cu 110	– (depends on Cu)	–	PI ~20–30	~Cu's (if Cu layer governs)	~Cu's (Cu layer thin, PI flexible)	E.g. 10 μm Cu + 25 μm polyimide: composite density ~2.8. Conductivity mainly from Cu.
Cu with C coat	8.96 (base)	~110 (base)	~1.8 (effective)	~95%	~16	~same as Cu	~same as Cu	2–5 μm carbon layer ㊱ negligible effect on bulk ρ, but drops contact R by ~5× (71) .
Cu with Sn coat	8.96 (base)	–	~1.7 (bulk)	~100%	~16	~same as Cu	~same as Cu	Thin Sn (~1 μm) won't affect Cu's ρ notably. Sn forms alloy with Li, aids plating.

Notes: "–" indicates not applicable or not a single value (as with carbon's anisotropic resistivity). Data above are representative – actual values vary with temper, thickness, etc. Sources include【3】Suragus (conductivity),【35】Special Metals (Ni foil),【16】ChargedEV (Cu alloys), and material datasheets.

Table A2 – Common Negative-Side Interlayer Coatings and Functions

Interlayer Type	Typical Thickness	Primary Purpose(s)	Notes & References
Carbon coating on Cu/ Al (graphitic or amorphous carbon, often in PVDF binder)	1–5 µm [90]	- Enhance electrical contact (reduce contact resistance) - Prevent native oxide interference - Improve adhesion with electrode	Lowers interface resistance dramatically [9] . Must be thin to not add weight. Hydrophobic – careful with water-based processes [50] .
Conductive polymer coating (e.g. PEDOT, polymer-graphene mix)	0.1–1 µm	- Improve flexibility (acts as buffer) - Provide conductive network on surface - Corrosion protection	E.g. PEDOT:PSS on Cu acts as anti-corrosion layer and keeps contact if Cu expands slightly. Can degrade at high temp.
Metal lithiophilic layer (Sn, Zn, Ag, Au, Li–In alloy, etc.)	50 nm – 5 µm (often ~0.1–1 µm)	- Seed uniform Li plating (reduce nucleation overpotential) - Barrier between Li and base metal (prevent alloying or dissolve)	Sn: commonly studied, forms Li_xSn alloy that is softer and guides plating [10] . Ag: high-cost, ensures even Li spread (Ag-Li has very low overpotential). Au: very effective but costly [14] .
Inorganic solid electrolyte coating (LiPON, Li_3N, LiF, LLZO nano-layer etc.)	50 nm – 1 µm	- “Artificial SEI” to prevent dendrites - Chemically isolate metal from liquid electrolyte (if used) - Improve ionic interface (in solid-state)	Must be thin enough to allow electron or ion tunneling. LiPON ~100 nm on Cu can stop electrolyte corrosion but adds ~100 $\Omega \cdot cm^2$ interfacial resistance until lithium wets it. Often used on Li metal rather than Cu.
Oxide layer (ALD Al_2O_3, TiO_2, etc.)	5–50 nm	- Passivate surface (anti-corrosion) - Promote uniform SEI formation - Enhance adhesion (some metal oxides bond to polymers)	ALD Al_2O_3 5 nm on Cu: increases polarization resistance by up to 100× in aqueous tests [34] . In cell, likely fractures to form Li–Al–O compounds that become part of SEI. Safe, but too thick a coating can raise initial impedance.
Nanocarbon interlayers (CNT, graphene, carbon nanowalls)	100 nm – few µm (height of CNTs)	- Increase contact area & elasticity - Conduct electrons efficiently across interface - Act as micro “springs” to buffer volume changes	E.g. vertically aligned CNT carpet ~5 µm on Cu: improves rate performance of Si anode, and retains 80% capacity vs 60% for no CNT in tests [60] [63] . Needs good anchoring (often grown directly on foil by CVD).

Interlayer Type	Typical Thickness	Primary Purpose(s)	Notes & References
Silane coupling layer	Monolayer (nm-scale)	- Improve bonding between metal oxide surface and binder (organic)	Used when electrode binder is water-based (e.g. CMC). A silane (like 3-aminopropyltrimethoxysilane) can be applied to oxidized foil, creating chemical bonds to both metal and binder, thus raising peel strength. Not commonly cited in battery lit, but used in other composites.
Lithium-containing wetting layer (e.g. Li–Mg alloy flash)	a few µm	- Provide immediate lithiated surface on Cu to avoid first-cycle lithium loss - Enhance Li spreading at initial plating	Anode-free strategies: evaporate a tiny Li–Mg or Li–In alloy on Cu to “pre-lithiate” it. This sacrificial layer consumes initial SEI formation and leaves a lithiophilic matrix. Reference [5] in some review indicates such coatings improve Coulombic efficiency.

Each interlayer must be assessed for compatibility: e.g., polymer or carbon may decompose above certain voltage, metal coatings might introduce new side-reactions (Sn will expand on alloying, need to stay adherent), and ceramic coatings could crack on bending. The choice often pairs with the collector material (Al foils almost always get carbon-coated in commercial cells [61] ; Cu foils for Li metal often get Sn or Ag coated in research).

8. Limitations & Disclaimer

This report provides a generalized, current (as of 2025) comparison of negative-side collector materials and interface treatments, drawing from literature and industry data. **It does not account for proprietary or unpublished advancements** that may further alter trade-offs (e.g. novel alloys or coatings in development). Performance values (electrical, mechanical, etc.) are given for standard conditions (room temperature, initial state); real battery operating conditions (e.g. 60 °C, after 1000 cycles) can shift these values. **Ranges are provided** where sources differ; engineers should consult specific supplier datasheets and test under their exact conditions for design decisions.

All safety-related discussions are generic – **any handling of active battery materials or new collector materials must follow your organization’s EHS protocols and safety data sheets.** For instance, switching to a stainless steel collector in a line set up for copper may require new tooling and insulation checks due to different hardness and spring-back. Always validate compatibility with existing assembly/welding equipment when considering new materials.

Finally, while efforts were made to ensure accuracy via reputable sources, some data (especially those marked by wide ranges) may depend strongly on purity, metallurgical state, measurement method, etc. It is advised to use this document as a **comparative guide** and not an absolute specification sheet. Performance in a cell can be influenced by many integration aspects beyond the collector (e.g. electrolyte additives affecting corrosion, pressure application, etc.).

Disclaimer: The author and publisher assume no liability for the use of this information. It is intended for research and educational purposes for engineering professionals. Implementation of any new material should undergo proper testing, safety review, and qualification in the specific battery context it will be used. Always refer to the latest standards (ASTM, IEC, JIS) for material testing and to OEM requirements for qualification criteria.

“When in doubt, test it out” – interface stability is crucial, and there is no substitute for real-world experimentation alongside theoretical analysis.

9. References

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