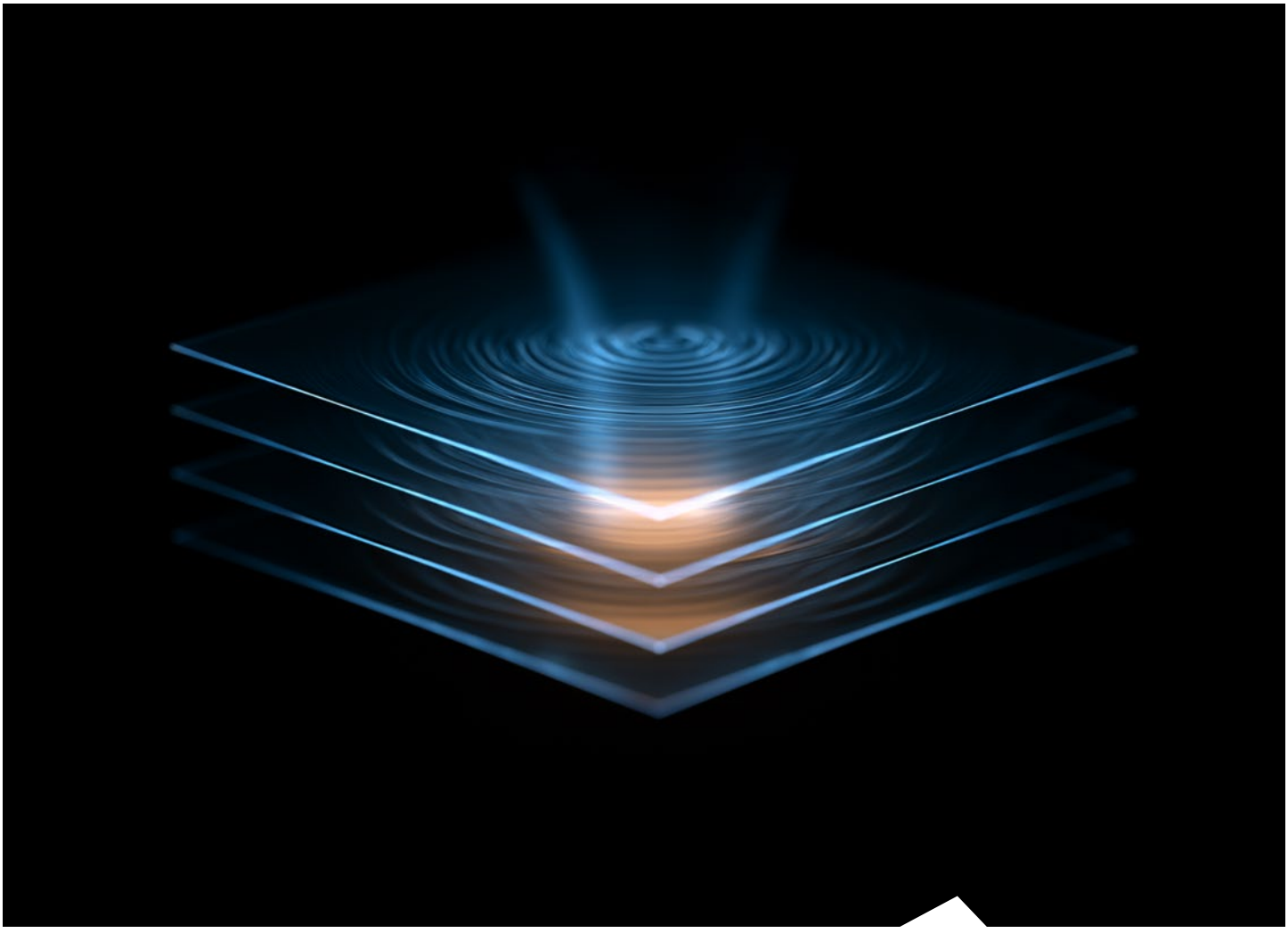
NANOLAYER

WHITEPAPER

ENGINEERING NEW FILM CAPABILITIES THROUGH NANOLAYER ARCHITECTURE

How Nanolayering Can Create Unprecedented Film Performance at Standard Production Cost



CONTENTS

EXECUTIVE SUMMARY

Peak Nano Systems' nanolayering process fundamentally changes how polymer films are designed and perform. Rather than waiting years for new polymer chemistry and materials to deliver incremental performance gains, Peak's NanoPlex™ technology creates transformative film properties—in weeks to months—using commercially available resins and standard extrusion manufacturing equipment.

The core innovation is elegantly simple: by coextruding dozens to thousands of alternating nanoscale polymer layers, each as thin as 25 nanometers, Peak Nano induces confinement-driven interphase/interdiffusion, which enables structural film properties otherwise impossible to achieve through conventional layering or blending.

Some examples of the new capabilities enabled by nanolayering include:

- **Improving oxygen-barrier performance** through confined crystal formation, targeting an EVOH replacement for recycling or biodegradability.
- **Enabling polypropylene-based dielectric films** to operate reliably 30°C above standard BOPP (Biaxially Oriented Polypropylene).
- **Increasing dielectric film breakdown strength** and energy density through interfacial barrier effects.
- **Transforming brittle polymers into tough and ductile** nanolayers to increase processability, handling, and usability.
- **Eliminating tie layers**, specialty adhesives, or expensive new chemistry in immiscible multilayer polymer films.

25nm
THINNEST
INDIVIDUAL
LAYER

This white paper describes the science behind nanolayer confinement, how the biaxial orientation processes can further augment emergent material properties, the elimination of tie layers and adhesives, and the economic advantages that make this technology immediately deployable across existing production infrastructure with minimal capital investment.

1000s
OF ALTERNATING
LAYERS
PER FILM

THE LIMITATIONS OF CONVENTIONAL FILM TECHNOLOGY

For decades, the polymer film industry has relied on a well-understood development formula: select the right polymers, combine/layer them in the right sequence, and bond them together with adhesives or tie layers. Traditional multilayer films typically comprise of 3 to 11 layers delivering predictable, additive properties. Each layer contributes its known properties to the overall structure according to the rule of mixtures. A barrier layer provides gas or water resistance based on the volume percentage of the high-barrier material. A structural layer provides strength, such as toughness or puncture resistance. An adhesive layer provides sealability and tack based on thickness. The result is a composite of which total performance is essentially the sum of its parts.

This approach has served the packaging, electronics, medical, and industrial film markets well, but it imposes fundamental constraints.

- Achieving new performance levels typically requires costly development of new polymer chemistry and subsequent manufacturing scaling processes that can take a decade or more from lab to commercial availability.
- Combining dissimilar polymers requires tie layers or adhesives, which add cost, complexity, and environmental concerns.
- The maximum performance of a layered structure is capped by the inherent properties of its constituent materials at their relative amounts.

Peak Nano's nanolayering technology breaks through all three of these constraints simultaneously.

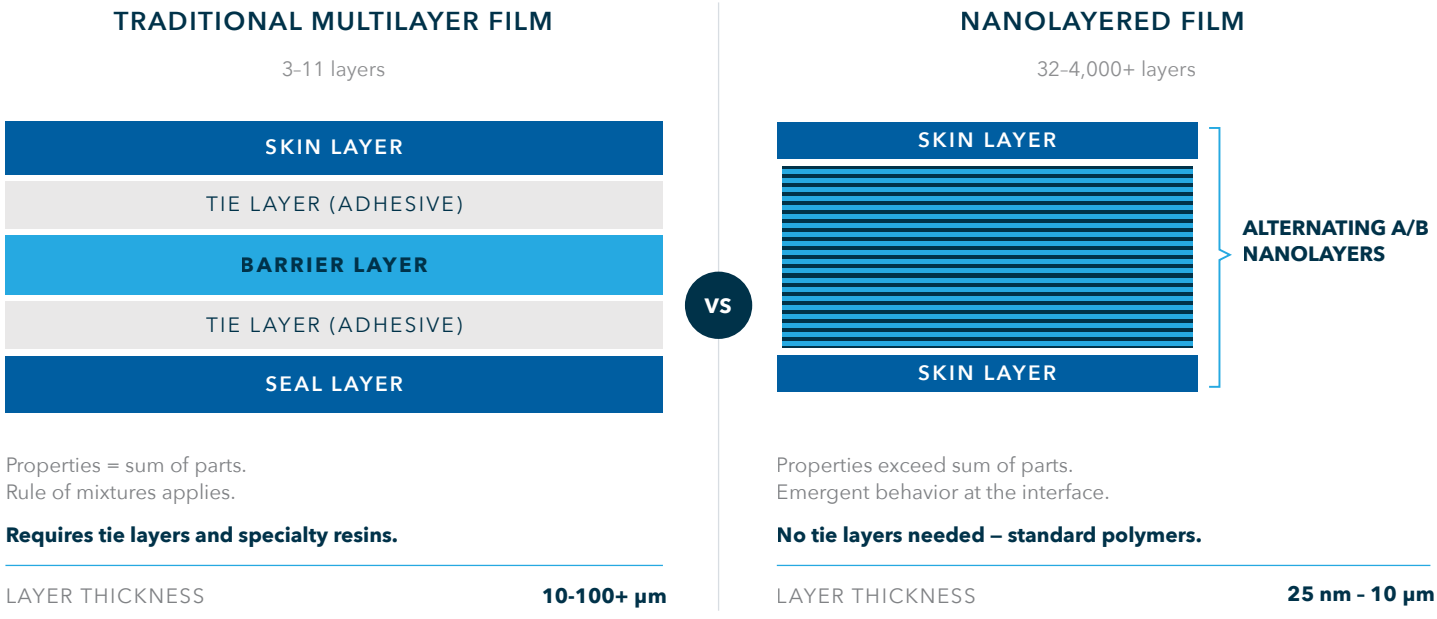


Figure 1: *Traditional multilayer films follow the rule of mixtures, while nanolayered films exhibit emergent properties that exceed the sum of their components.*

THE SCIENCE OF NANOLAYER ARCHITECTURE

Nature's Blueprint: Layered Structures in the Biological World

The concept of achieving extraordinary material properties through nanoscale layering is not an invention; it is a discovery. Nature has employed layered polymer and mineral structures for hundreds of millions of years to produce materials with performance characteristics that far exceed those of their constituent components individually.

- Nacre (mother-of-pearl), for example, is composed of alternating layers of brittle aragonite and soft biopolymer yet exhibits fracture toughness approximately 3,000 times greater than monolithic aragonite.
- The iridescent wings of the Morpho butterfly achieve their vivid coloration not through pigments but through nanoscale-thick alternating layers of chitin that selectively reflect specific wavelengths of light.
- The golden appearance of the Anoplognathus parvulus beetle exoskeleton contains graded cuticle layers with thicknesses ranging from 200 nm to 50 nm, producing broadband optical reflection across the visible spectrum.

These biological examples demonstrate a principle that Peak Nano has translated into industrial practice: when materials are organized into repeating layered architectures at the nanoscale, the resulting structures exhibit properties that are not merely additive but synergistic—a direct consequence of the physical confinement and interfacial effects that dominate at these length scales. The earliest industrial applications of multilayered polymer systems date to the 1970's, when multilayer polymer and foil tubes replaced metal toothpaste packaging due to corrosion issues. Over the subsequent five decades, the science and engineering of multilayered polymers have advanced to the point where Peak Nano can now produce films with layer thicknesses approaching those found in nature's most sophisticated optical and structural materials.

THE NANOLAYERED PARADIGM SHIFT IN FILM STRUCTURE

As shown in Figure 1, a conventional film might contain 3 to 11 layers, with individual layer thicknesses on the order of tens of microns. A nanolayered film contains 32 to over 4,000 layers, with individual thicknesses ranging from 10 microns down to 25 nanometers. However, nanolayered films differ from traditional multilayer films not merely in the number of layers possible, but in the fundamental physics governing their behavior.

This distinction is not academic. When polymer layers are confined to thicknesses below approximately 250 nanometers, the physical constraints imposed by adjacent layers fundamentally alter how polymer chains organize, crystallize, and interact. The confined geometry forces change in crystalline morphology, chain orientation, and interphase and interfacial behavior that produce emergent properties—properties that are not merely enhanced versions of bulk material properties, but qualitatively new behaviors arising solely from the nanoscale architecture.

These effects have been extensively documented in over 40 years of academic and industrial research, much of it originating from Case Western Reserve University and subsequently commercialized by Peak Nano Systems. The foundational science has been published in peer-reviewed journals and compiled in the reference text by Langhe and Ponting[1], which remains the definitive resource on manufacturing and applications of multilayer polymer films.

THE LAYER MULTIPLICATION PROCESS

The nanolayered film-production process uses a combination of conventional coextrusion extruders with either a microlayered feed block[2] or with the addition of a series of sequential-layer multiplication dies. Peak Nano's NanoPlex technology creates nanolayered films through a coextrusion and layer multiplication process, also referred to as split and stack (see Figure 2). Two or more polymer melts are fed from conventional extruders into a specially designed feed block, which forms an initial layered structure of alternating polymer streams. This initial layered melt then passes through a series of layer-multiplying dies—each of which doubles the number of layers by splitting the flow, stacking the halves, and recombining them. The sequential-layer multiplier design creates a highly flexible coextrusion process for producing polymeric films with tens to thousands of layers with simpler tooling changes for development and pilot lines.

The mathematics are straightforward: if n represents the number of multiplying elements, the resulting structure contains 2^(n+1) layers. For example, 10 multiplying elements yield 2,048 layers. The total film thickness is determined by downstream processing, die gap, draw ratio, and optional biaxial stretch ratios, while the number of layers and their individual thicknesses are independently controlled by the number of multiplying elements and the volumetric feed ratios of the constituent polymers.

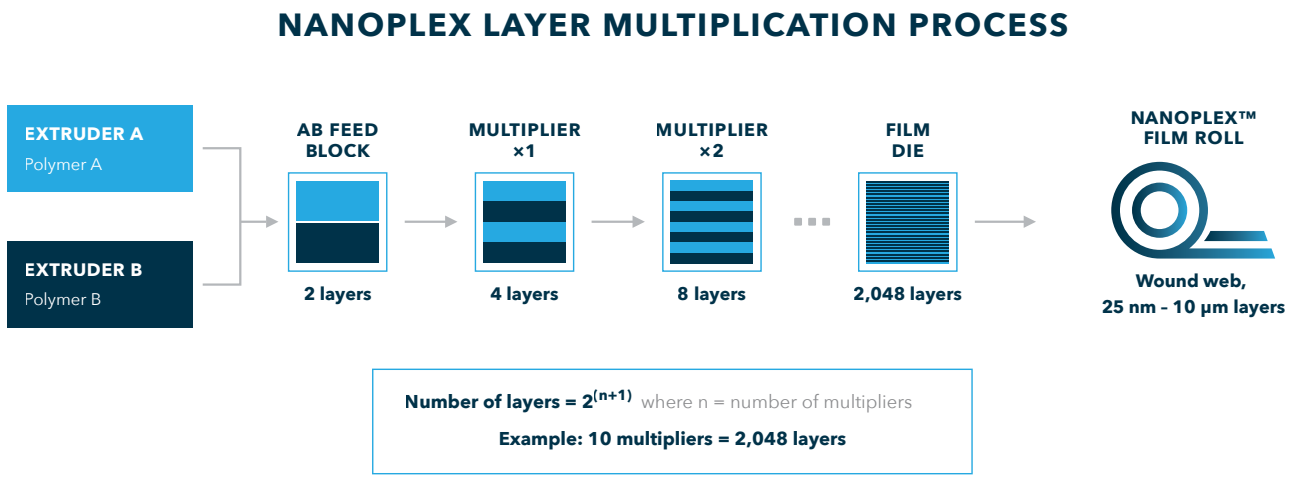


Figure 2: *The Peak NanoPlex layer multiplication process converts standard polymer feedstocks into films with dozens to thousands of precisely controlled nanolayers.*

Critically, the layer multiplication occurs in the melt state, within existing extrusion tooling. The extruders, melt pumps, film dies, chill rolls, and winding equipment are all standard commercial units. Only the feed block and multiplier dies are added to the system to enable this technology, which is a one-time capital cost and not a product cost increase. This means that any existing film production facility can be retrofitted to add nanolayer capabilities with minimal capital expenditure.

Material Versatility

Peak Nano's coextrusion process has been demonstrated across virtually the entire palette of commercial thermoplastic polymers.

Successful nanolayer structures have been fabricated with:

- Polyolefins (PE, PP, COC/COP)
- Nylons
- PET
- EVOH
- Polycarbonates
- Polysulfones
- Fluoropolymers
- Acrylics
- Styrene-based polymers
- TPUs
- ABS
- Liquid crystal polymers
- Block copolymers
- Cellulose-based polymers
- Biodegradable and bio-sourced polymers
- Recycled polymer streams and filled polymer systems

FURTHER ENHANCING NANOLAYER PROPERTIES

The Role of Biaxial Stretching

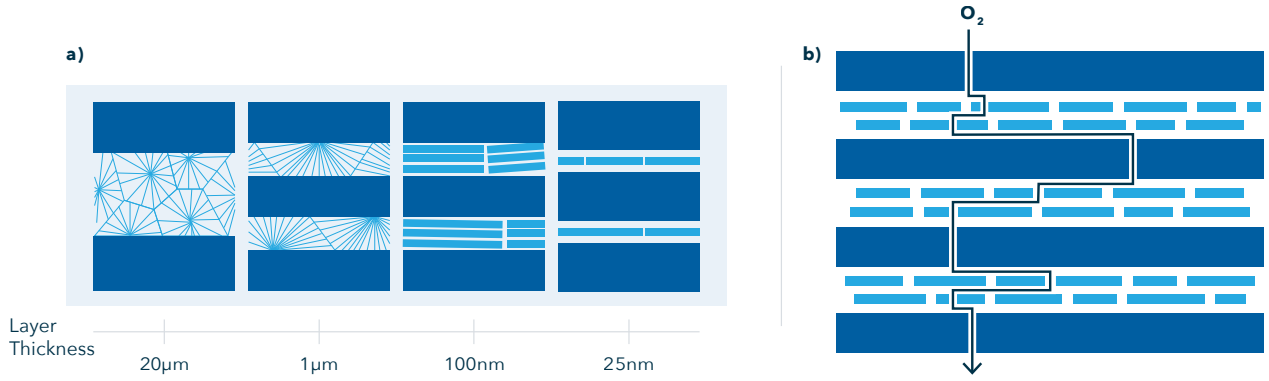
While the coextrusion and layer multiplication process creates the nanolayered architecture, adding subsequent biaxial orientation can further activate the most dramatic property enhancements. Biaxial orientation is the process of stretching a film in both the machine direction (MD) and the transverse direction (TD), and is a well-established commercial technique for producing BOPP, BOPET, and other oriented films. What is new is the application of biaxial stretching to nanolayered precursor films, in which the confined geometry of the nanolayers induces unique crystallization behavior during and after orientation.

Confinement-Induced Crystallization

In a conventional polymer film, semi-crystalline polymers form three-dimensional spherulitic structures during cooling. These spherulites are essentially random clusters radiating outward from nucleation points. Their size, orientation, and density are functions of cooling rate and polymer chemistry, and their contribution to film properties follows conventional models.

When a semi-crystalline polymer is confined within a nanolayer thin enough that its thickness approaches the dimensions of individual macro-crystals, the spherulitic growth habit is physically suppressed. The confined geometry forces the polymer chains to crystallize into a dramatically different single- or stacked-lamellar morphology that are highly oriented parallel to the film surface, thereby enhancing many desirable film properties.[3] This transition from random 3D spherulites to ordered 2D in-plane crystals is the mechanism responsible for the extraordinary enhancements in properties observed in nanolayered films.

CONFINEMENT-INDUCED CRYSTALLIZATION



EMERGENT PROPERTIES FROM NANOCONFINEMENT

BARRIER	MECHANICAL	THERMAL	ELECTRICAL
Up to 100× lower O_2 permeability vs. polyethylene	Brittle → tough; enhanced elongation	Higher heat capabilities; stable to 135°C+	Higher dielectric constant; 50% lower dissipation

Figure 3: *(a) As layer thickness drops from micron to nanometer scale, crystal morphology shifts from spherulites to stacked in-place lamellae and finally single crystals. (b) Single crystal stacking creates a tortuous path for oxygen molecules to travel through the film.*

Literature examples [4,5,6] show that confining semicrystalline polymers such as PCL, PEO, PET, and PPS into nanoscale layers can enhance structure and/or operating temperatures. Further alignment of PCL and PEO through biaxial orientation of the film was confirmed with wide-angle X-ray scattering (2D-WAXS) —structures that are qualitatively different from anything achievable through conventional film processing. This is not simply a matter of "more stretching" or "more layers". The confined crystallization phenomenon is a true phase transition in the material's organizational behavior, occurring only when layer thicknesses are reduced below a critical threshold, typically around 250 nanometers.

This change in PCL and PEO material-crystallization behavior through nanolayering has shown large reductions in oxygen transport behavior. The mechanism for the reduction in gas permeation through the confined, layered polymer film can be attributed to an increase in tortuosity of gas molecules diffusing through the film. The crystalline phases restricts molecular-gas transport to mainly around the crystalline domains or through disordered gaps. The amount of crystallinity and lamellar orientation can be controlled by varying the layer thickness in the nanolayered films and controlling the size and spacing of these gaps to reduce gas permeation.

ELIMINATION OF TIE LAYERS AND BONDING POLYMERS

One of the most commercially significant consequences of nanolayering is the elimination of adhesive tie layers traditionally required to bond dissimilar or immiscible polymers in multilayer film structures. In conventional films, polymers that are chemically incompatible, for example polyethylene and Nylon, require a maleic anhydride-grafted or similar tie layer to achieve adequate interlayer adhesion. These tie layers add cost, require additional extruders—which adds process complexity—and limits the design freedom of the film structure.

In a nanolayered structure, the physics of interlayer adhesion change fundamentally. When individual layers are reduced to nanoscale thicknesses, the ratio of interfacial area to bulk volume increases dramatically. The alternating A/B/A/B architecture means that each thin layer of an incompatible material is effectively "sandwiched" between layers of the base material. The cumulative adhesive forces across hundreds or thousands of these interfaces, combined with the mechanical interlocking that occurs as confined layers crystallize and orient, provide sufficient structural integrity to frequently eliminate the need for dedicated adhesive layers .

This has profound practical implications. Film designers gain the freedom to combine polymers that were previously considered incompatible, opening new design spaces for barrier, optical, electrical, and mechanical optimization. Manufacturing lines can be simplified, as the number of extruders required for a given film structure is reduced. And material costs decrease, as expensive tie-layer resins and adhesives are removed from the bill of materials.

Peak Nano has demonstrated tie-layer-free bonding across a wide range of polymer combinations, including polyolefin/engineering polymer systems, fluoropolymer/hydrocarbon systems, primary/recycled polymer systems and biodegradable/conventional polymer systems. In each case, the nanolayer architecture provides adequate adhesion through confinement effects alone, without any chemical modification of the constituent polymers.

This capability is directly relevant to sustainability objectives as well. Many high-performance barrier films rely on complex multi-material structures that are difficult to recycle because adhesive layers bond dissimilar polymers. Nanolayered technology creates design possibilities that simplifies the film composition and allows for recycle-ready materials. Peak Nano is actively developing nanolayered structures using recycled, bio-sourced, and biodegradable polymer streams, further expanding the technology's sustainability profile.

THE PHYSICS OF INTERLAYER ADHESION CHANGE FUNDAMENTALLY AT NANOSCALE THICKNESS.

THE ECONOMICS OF NANOLAYERING:
PERFORMANCE WITHOUT COST PENALTY

Perhaps the most compelling aspect of Peak Nano's technology is its economic profile. Unlike most advanced materials technologies, which typically require expensive new feedstocks, dedicated production equipment, or specialized processing conditions, nanolayering delivers dramatically enhanced performance using standard materials and standard equipment, with minimal incremental capital cost and no increase in operating cost.

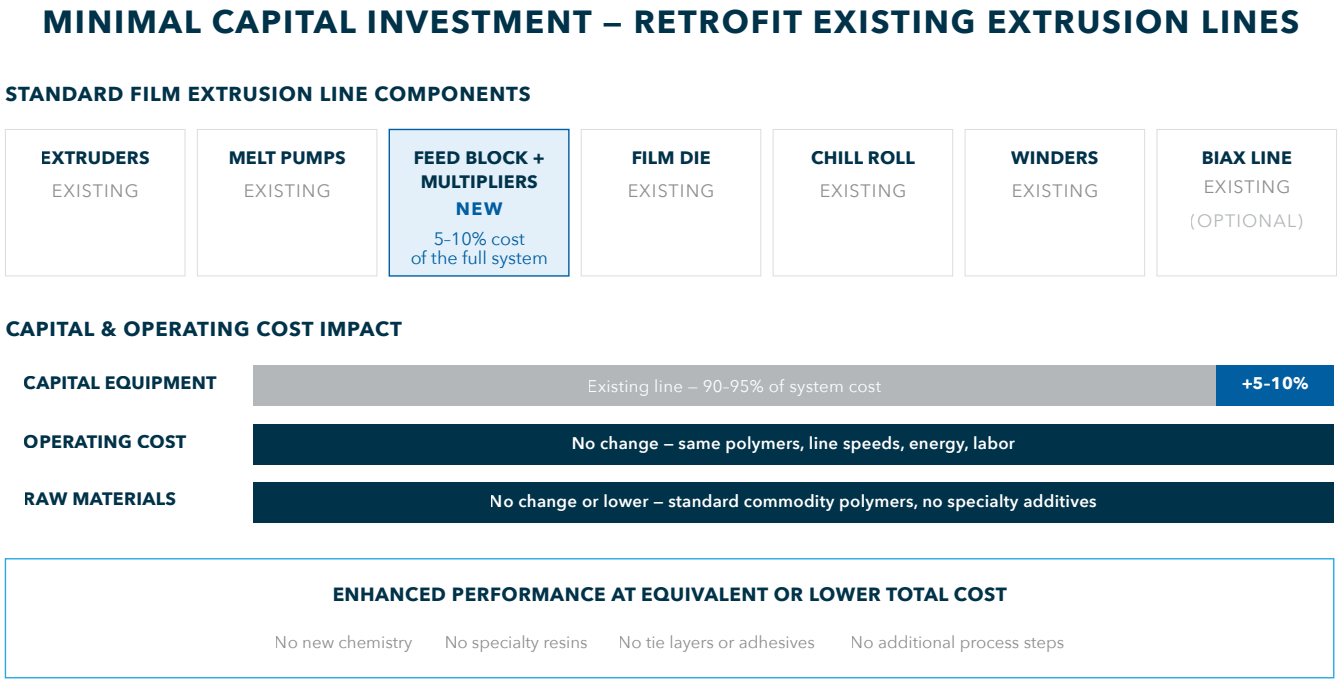


Figure 4: *Nanolayering requires only the addition of a feed block and layer multiplying dies to an existing extrusion line– typically 5-10% of the total system capital cost.*

Nanolayered Capital Equipment

Converting an existing film extrusion line to nanolayer capability requires only the addition of a feed block and layer-multiplying die elements. All other equipment, extruders, melt pumps, film dies, chill rolls, winders, biaxial stretching ovens, etc. remains unchanged. The additional capital cost is typically 5-10% of the overall extrusion system cost, making the retrofit economically feasible for virtually any film producer.

No Increase to Operating Cost

Because nanolayered films are produced using standard commercial polymers at standard processing temperatures, pressures, and throughput rates, the operating cost per kilogram of film produced is essentially unchanged. Energy consumption, labor requirements, maintenance schedules, and scrap rates are comparable to those of conventional multilayer film production. The feed block and multiplying dies operate passively—they have no moving parts, require simple heating, and add negligible pressure drop to the extrusion system.

Standard Material Cost

Nanolayered films use the same base polymers that are already in commercial use. No specialty resins, nano-additives, or proprietary chemical formulations are required. In many cases, product costs decrease because tie layers and adhesive resins are eliminated from the bill of materials. For barrier applications, expensive barrier polymers like EVOH can be replaced or their volume fraction significantly reduced, as the nanolayer confinement effect amplifies their effectiveness. For capacitor films, standard engineering thermoplastics replace more expensive, specialty films that are now becoming increasingly limited in the market.

PEAK NANO'S FILMS-AS-A-SERVICE DEVELOPMENT PROCESS

Peak Nano operates as a strategic innovation partner, working collaboratively with customers to engineer nanolayered film solutions tailored to specific application requirements. The development process follows a structured workflow designed to move from concept to validated prototype in weeks and months rather than years typical of new material development programs.

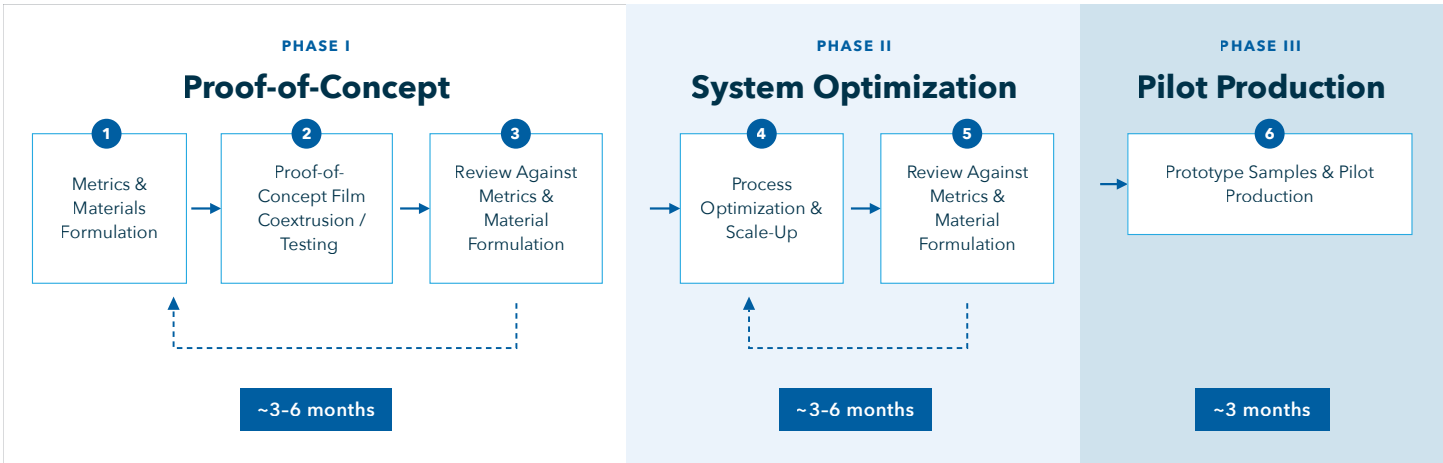


Figure 5: *Peak Nano's Films As A Service structured development workflow moving from concept to pilot production.*

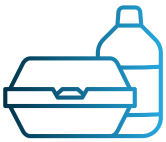
The process begins with a collaborative definition of performance targets such as mechanical, optical, electrical, barrier, regulatory, and sustainability requirements. Peak Nano's materials science team then selects candidate polymer systems from a proven library, designs candidate nanostructures (specifying layer count, thickness, order, and performance zones), and produces prototype films on in-house R&D and pilot lines. Testing and validation are

conducted at Peak Nano and/or customer facilities, with iterative refinement cycles typically requiring only one to two additional prototype runs to achieve target specifications.

Upon successful validation, Peak Nano delivers a complete technical transfer package including architecture and specification files, standard operating procedures and processing conditions, material sourcing information, IP and license disclosures, and recommended manufacturing partners. For customers requiring production support, Peak Nano offers in-house manufacturing options while also collaborating with select extrusion, slitting, and converting partners for pilot-to-commercial trials and toll production.

MARKET APPLICATIONS AND COMMERCIALIZATION STATUS

Peak Nano's nanolayer technology is currently deployed or in active development across multiple market segments, each benefiting from the same core platform of confinement-driven property enhancement. Peak Nano's food and medical packaging work runs through Films as a Service, a contract research program rather than a catalog of fixed grades. A packaging team brings its performance targets, its existing resins, and its line constraints; Peak brings the nanolayer coextrusion capability and the polymer science. Programs move through five stages: define the target; constrain the inputs to relevant or selected resins, suppliers, and converting equipment already qualified; design and extrude candidate structures on Peak's R&D and pilot lines; test, iterate, and converge against baseline specifications; and deliver the optimized structure with its process conditions and a scale-up path. First-generation prototype films run six to ten weeks from design approval, rather than the typical years long process for new resins.



Food Packaging

Food packaging programs to date target flexible formats where increased barrier performance, longer shelf life, and abuse resistance are required. Biodegradable and compostable structures are explored through Peak's research program rather than offered as shipping products. The program started in early 2026, focusing on PLLA, PCL, and PVOH for water and oxygen barrier in degradable films, building on previous proof-of-concept work. The near-term commercial contribution is material reduction and simpler, recycle-ready structures. Initial results will be published later this year. A main focus in food packaging for the last several years is the replacement of materials of concern. Current and future regulations are mounting, such as the EU PPWR restrictions on PFAS implemented in August. Twelve US states had restrictions on intentionally added PFAS in food packaging in force or scheduled as of April 2026, and state-level EPR programs add a further set of design constraints. Chlorinated barrier materials and foil laminates face parallel end-of-life pressure. Using new architecture to create sustained or improved properties using existing, approved polymer systems avoids potentially lengthy regulatory requalification that accompanies new chemistries.

Medical Packaging

Medical device packaging requires films that simultaneously deliver exceptional gas and moisture barrier, chemical resistance, mechanical toughness sufficient to survive handling and transport abuse, and optical clarity for visual inspection, all while meeting stringent regulatory requirements. For medical packaging specifically, the film must also withstand one or more sterilization methods, such as autoclave (steam), gamma irradiation, electron beam, or ethylene oxide (EtO), without degrading any critical property. Conventional multilayer films address these requirements through complex structures of five to nine layers, incorporating specialty barrier polymers. Nanolayered films can address these challenges through several mechanisms.

- Confinement-induced crystalline orientation produces films with significantly higher heat capabilities and reduced shrinkage at elevated temperatures.
- Nanolayered films of normally brittle polymers exhibit dramatic improvements in elongation and toughness at the nanoscale, with failure mechanisms shifting from catastrophic brittle fracture to ductile energy absorption, a property that is preserved after sterilization exposure.
- Replacement of fluorinated resins with nanolayered polymers while maintaining performance and processability.

Dielectric Capacitor Films

In the energy storage sector, Peak NanoPlex LDF capacitor film has launched and is deployed across defense, grid, transportation, and fusion energy applications. Its higher operating temperature (135°C vs. 105°C), lower dielectric losses at temperature, higher breakdown strength, and dramatically reduced shrinkage make NanoPlex LDF a drop-in upgrade for every application BOPP-C capacitor film serves today and opens up high-temperature power electronics applications that BOPP-C cannot serve at all.

Sustainability and Circular Economy

Nanolayering technology aligns with multiple sustainability objectives that are increasingly important to brand owners, regulators, and consumers. By enabling equivalent or superior film performance at reduced total thickness (downgauging), nanolayering directly reduces per-unit material consumption. The elimination of tie layers and adhesives simplifies film compositions, improving compatibility with existing recycling streams. The demonstrated ability to process recycled, bio-sourced, and biodegradable polymers via nanolayer coextrusion means the technology can be applied to the development of next-generation recycle-ready, sustainable packaging without sacrificing performance. Peak Nano is actively engaged in development programs targeting compostable barrier films, mono-material recyclable structures, and films incorporating post-consumer recycled content, all leveraging nanolayer confinement to achieve performance levels that these sustainable polymers cannot reach in conventional film architectures.

Other Areas to Explore

The nanolayer coextrusion platform opens a wide array of potential applications and new areas to explore. These include:

High chemical-resistant packaging for aggressive solvent, acid, and base environments.

Antimicrobial films that build protective function into the layer structure itself.

Ultra-low migration barriers for sensitive contents where trace transfer must be minimized.

Films for lamination that give converters an all-polymer alternative to foil, with added flexibility, lower weight, transparency for inspection, and better end-of-life recyclability.

THE NANOLAYERED ADVANTAGE

Peak Nano's patented nanolayering technology represents a fundamental advance in polymer film engineering. By creating precise architectures of hundreds to thousands of nanoscale-thin layers from standard commercial polymers and activating confinement-induced crystallization through standard biaxial orientation processing, Peak Nano delivers film performance that exceeds what is achievable through conventional multilayer design, polymer blending, or new chemistry development. The key advantages include:

- Nanolayering enables emergent properties: barrier, mechanical, thermal, optical, and electrical properties exceed the rule of mixtures due to confinement-driven phenomena.
- Tie layers are eliminated by nanoscale adhesion, enabling the bonding of immiscible polymers without adhesives.
- Peak's approach uses standard materials, relying exclusively on commercially available polymers rather than new chemistry.
- Minimal capital investment is required, with retrofitting existing lines costing only 5-10% more in capital equipment.
- Operating costs remain unchanged, with no increase in energy, labor, or material costs per unit of film.
- The development cycle is dramatically faster, delivering prototypes in weeks instead of years.

For film producers, converters, and OEMs seeking higher performance without higher cost or seeking to solve problems that conventional materials cannot address, Peak Nano's NanoPlex technology offers a proven, scalable, and economically compelling path forward.

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