ENGINEERING TECHNOLOGY WHITE PAPER

Plastic Optical Fiber (POF) Termini for Harsh-Environment Interconnect Systems

Engineering principles, development findings, performance evidence and application guidance for ARINC 801 and MIL-PRF-29504 architectures

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Prepared for aerospace, defense, avionics, spacecraft, cable-harness and optical-link design engineers.



Executive position

Plastic optical fiber provides a compelling option for selected aircraft, defense and spacecraft optical links when the cable, terminus, alignment interface and connector are engineered as an integrated system. XiOptics developed POF-compatible ARINC 801 and M29504 terminus architectures through a multi-year effort that included the POF for aircraft-network development program. The resulting technology portfolio spans the company's terminus families.

XiOptics retains proprietary control of its cable-to-terminus retention and processing technology. This paper deliberately does not disclose the process recipe, materials formulation, manufacturing parameters, detailed retention geometry or proprietary work instructions. XiOptics offers application engineering and finished terminated cable assemblies to customers.

1. Abstract

Adaptation of large-core polymer optical fiber to standardized high-density aerospace connectors creates a distinct set of integration problems. Polymer fiber diameter tolerance, core eccentricity, coefficient-of-thermal-expansion mismatch, end-face durability, vibration exposure, and mechanical cable retention collectively determine optical-link stability. The selection of a familiar connector housing does not remove these interactions.

The XiOptics development record spans early M29504 POF derivatives and subsequent ARINC 801 POF designs, including aircraft and space basednetwork research programs. The common engineering objective was to retain established interconnect interfaces while controlling environmental loss drift and maintaining serviceable, random-mate connections. Historic tests documented low-loss tuned prototypes, benefits of noncontacting end faces, and the consequences of contamination or geometry changes. They also demonstrate why design qualification must address the complete cable/terminus/connector assembly as a system, not a series of individual elements.

2. Scope and boundaries

This paper examines 1 mm-class polymer optical fiber, especially the step-index; other polymer chemistries, diameters, numerical apertures and graded-index variants require individual engineering review. It describes POF-enabled M29504 pin/socket termini and ARINC 801 keyed spring-loaded termini, related alignment elements, and system qualification considerations.

Included	Excluded / controlled information
System architecture, interfaces and performance mechanisms	Adhesive chemistry, surface preparation or cure recipe
Historical published-program objectives and reported observations	Detailed proprietary fiber/strength-member attachment method
Cable selection, end-face concepts and verification framework	Part-level manufacturing drawings and internal dimensions
Product configuration comparison and application guidance	Customer-specific confidential test articles or data

3. Technical terminology

POF: polymer/plastic optical fiber; GOF: glass optical fiber; IL: insertion loss; AG: air gap; PC: physical contact; FOD: foreign-object debris; random mate: connection of independently produced and controlled optical assemblies without pair-specific matching; pistoning: axial movement of the optical medium relative to its ferrule or cable support.

4. Development background and program objectives

The aircraft-network POF initiative provided a principal development driver for broadening XiOptics POF capabilities. The engineering direction was to avoid creating an entirely new connector ecosystem and instead enable established circular and rectangular platforms by modifying the optical terminus and, where necessary, alignment sleeve interfaces. This protected connector availability, installation infrastructure, service practices and supply-base diversity.

The historical program requirements included low life-cycle cost, robust field termination, high environmental endurance and optical performance suitable for high-volume airframe production. Early design presentations identified 0.6 dB initial IL with no more than 0.4 dB environmental variation as an engineering objective. A later procurement requirement specified 1.0 dB maximum loss for a mated POF channel. These numbers are not interchangeable: one is a development target and the other a specified acceptance limit for a particular program phase. [S1, S2, S3]

4.1 Progression across multiple architectures

The initial activity was focused entirely on Mil-C-38999 circular connectors with POF integration, XiOptics lead the effort with derivative M29504 /4, /5, /6 and /7 product structures. Ultimately, for commercial aircraft the technology progression lead to an ARINC 801 development that emphasized ferrule structural margins, a keyed anti-rotation system and a compatible alignment sleeve for larger-diameter POF-carrying ferrules. Public product-family breadth today should not be confused with the test scope represented by each historical document.

Program stage	Engineering focus	Evidence status
M29504 POF	Use standard-size contact cavities; support pin/socket and multiple connector formats	Prototypes, field samples and historical qualification-related reports
ARINC 801 POF	Keyed carrier, axial spring compliance, alignment sleeves and end-face design	Development hardware and selected bench/environmental observations
Current XiOptics portfolio	POF-capable derivative termini across company families	Product availability stated by XiOptics; application-specific supporting files required

5. POF as an optical transmission medium

Large-core POF permits comparatively generous geometric coupling, rugged handling and simple source/detector packaging for appropriate link lengths. These benefits do not eliminate interface loss: the finite diameter tolerance of the polymer core/cladding, the relative optical-center position, and changes of the launched mode distribution remain important in a tightly controlled multi-channel optical network.

For a 1 mm-class step-index design, the source documents discuss a nominal approximately 980 µm core and 1000 µm cladding with historical cable tolerances as large as ±50 µm. Such values illustrate how the nominally large core size still produces a meaningful random-mate misregistration envelope. They are historical program input assumptions, not universally applicable POF specifications. [S2, S3]

5.1 Optical budget fundamentals

A link budget must include source launch power, propagation attenuation at the selected wavelength, all connector interfaces, installation allowances and end-of-life margin. Insertion loss at a mating interface is not a single fixed attribute of the terminus: optical launch condition, end-face geometry, core positioning and contamination can change the measured result.

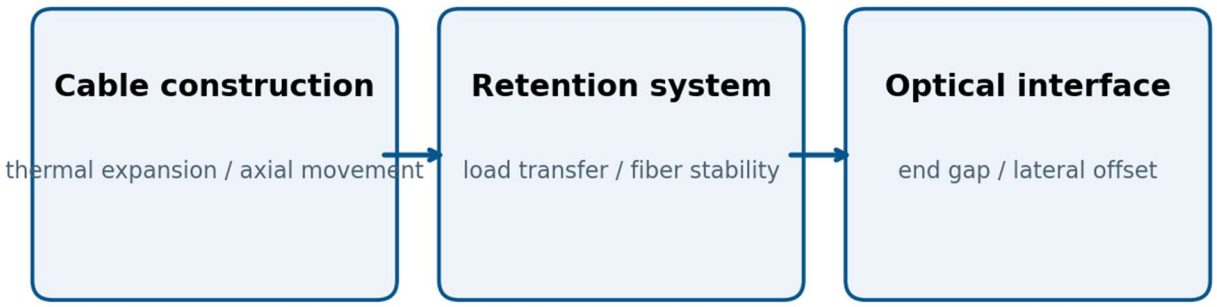
Simplified engineering accounting: $IL_{link} = \Sigma IL_{mated\ interfaces} + \alpha(\lambda,T)L + IL_{other} + margin$, where α denotes cable attenuation per unit length, L represents routed length, and the component values are defined for the measurement conditions. For actual POF networks, modal conditioning and source geometry should be controlled during testing.

5.2 Key fiber-specific risks

- Radial mismatch and dimensional eccentricity across the cable and ferrule build.
- Differential thermal expansion and movement of the fiber relative to its cable jacket.
- Sensitivity of exposed polymer end faces to physical rubbing, contamination and wear.
- Variation in optical mode distribution with cable bend radius, connectors and launch optics.
- Polymer chemistry, moisture uptake and thermal-aging limits specific to the selected POF product.

6. Harsh-environment termination: the governing engineering problem

The dominant mechanical challenge is keeping the polished optical interface stable while the cable structure carries external loads and experiences differential thermal movement. Cable jacket, reinforcement and polymer optical medium can have materially different coefficients of thermal expansion and different mechanical relaxation behavior. In an improperly integrated assembly the fiber can piston, the optical end gap can close or grow, and lateral centering can shift during thermal cycling.



An aerospace-capable POF terminus must therefore provide a validated load-transfer and fiber-positioning architecture. The requirement is functional: externally applied loads should not be allowed to translate unpredictably into the alignment interface. The details of how XiOptics achieves that retention remain proprietary and are not disclosed in this paper.

6.1 Why mechanical gripping alone may be insufficient

Historical development experiments reported that some early crimp/swage-only candidates did not simultaneously achieve required retention force and acceptable thermal pistoning behavior. The historical documents cite retention falling to approximately 5 lbf in some early configurations, but those values are not universal failure limits for mechanical retention. The resulting engineering decision was to retain a controlled architecture capable of stabilizing the POF medium and cable as a system. [S3, S5]

6.2 Environmental qualification is assembly-specific

A qualified metallic shell or glass-fiber terminus is not by itself evidence that a new POF, jacket and termination combination is qualified. The actual combination with POF media must be verified for retention, optical stability, cable compatibility, servicing and environmental performance. XiOptics spent nearly 10 years proving such in its efforts to bring to market a usable avionics POF interconnect solution.

7. M29504 POF terminus family

XiOptics developed POF-capable forms based on the established M29504 pin/socket architecture. Historical design records reference /4 and /5 configurations for MIL-DTL-38999-class circular connectors, /6 and /7 configurations for selected rectangular interconnects, and further cavity-specific derivatives. These designs offered a cost-effective route to POF adoption while preserving available connector hardware and familiar support tools. [S1, S4, S5]

7.1 Pin/socket interface and mechanical behavior

A fixed pin and spring-supported socket create an optical reference geometry distinct from the genderless, dual-spring configuration used in ARINC 801. This influences mating loads, alignment-hood implementation, contact compliance and the disposition of cable forces. Selection must be made at the connector assembly level, not on the terminus outline alone.

7.2 Benefits and application constraints

Potential advantages	Engineering considerations
Existing military and aerospace connector installed base	Cavity alignment depends on shell/insert supplier and arrangement
Availability of established insertion/removal toolsets	Random-mate data needed for actual pin/socket combination
Potentially favorable system-level cost	Optical hood/sleeve materials and end-face cleanliness require control
POF family variants for multiple connector platforms	Cable retention must be matched to jacket and reinforcement construction

7.3 Product experience

Earlier XiOptics materials were proven with delivery of thousands of POF M29504 termini for evaluation and applications and extensive operational experience with the underlying GOF product architecture. XiOptics now delivers substantial ongoing POF M29504 products in flying avionics and space programs. The POF solutions offered by XiOptics illustrate not only the POF terminus but the overall interconnect body, POF terminus and POF termination methods.

8. ARINC 801 POF terminus family

The XiOptics ARINC 801 POF program adapted a keyed, spring-loaded ferrule-carrier architecture for large-core POF while retaining compatibility with the intended ARINC 801 connector ecosystem, subject to the specific alignment sleeve/insert configuration. A later development proposal specified a larger metallic ferrule than conventional 1.25 mm glass ARINC 801 termini. Such variants require matching sleeve geometry; a larger-ferrule POF design must never be assumed to fit an unmodified standard glass-fiber alignment sleeve. [S2, S3]

8.1 Dimensional registration and optical stability

The historical engineering rationale emphasized controlling relative rotation between the polished optical medium and its mating interface. A keyed carrier can offer discrete angular adjustment during production, allowing control of the core eccentricity direction relative to a defined reference. This improves the probability of low-loss random mating but does not cancel all optical error mechanisms for every possible pair.

8.2 Separation of external anti-rotation features

A second key architectural principle is preventing connector-body anti-rotation contact loads from imposing unintended frictional restraint on the translating ferrule carrier. Smooth, repeatable axial compliance is important to end-face positioning and environmental stability. The specific internal XiOptics implementation remains proprietary; the design objective is described here only at a functional level.

8.3 ARINC 801 application selection

Use of this family should likely be taken only when the platform already employs the relevant ARINC 801 inserts, high-density optical routing requires consistent channel geometry, and the chosen POF ferrule/sleeve combination has been jointly validated. POF in ARINC801 termini has been shown to be successful but it does require specialized connectors where-as other M29504 solution demonstrated that they can be used in standard low cost Mil-C-38999 connectors including mixed mode and across a fully range of sizes and materials. The selection should include mating force, sleeve materials, debris generation, cable retention and applicable service tools.

9. End-face geometry: durability versus optical efficiency

Unlike silica glass, a polymer optical end face is relatively susceptible to damage from repeated physical rubbing. During the historical POF terminus development work, the design teams examined physical-contact and air-gap architectures to preserve optical transmission during vibration and maintenance cycling.

9.1 Noncontacting end-face strategy

The development data showed that noncontacting end-face configurations providing an intentional micrometer-scale separation between mating polymer surfaces could and do function quite well without impact optical performance significantly. Historical undercut/gap concepts in the range of approximately 10–80 µm were evaluated, and a separate program attempted to utilize a nominal 50 ± 10 µm gap before test results discouraged this solution. [S2, S3, S4]

An air gap introduces optical reflection and longitudinal-separation loss, but may reduce abrasive contact, micro-crazing and debris during vibration. The best choice depends on the end-face geometry, wavelength, NA, sleeve design and optical power budget. A noncontacting design is not automatically low loss: it must preserve core registration and a consistent axial gap. XiOptics developed a proprietary polish solution of terminus materials, surface finishes, polish media and test/evaluation at the time of termination to deliver a world class solution to the harsh environment POF requirements.

9.2 Physical-contact design tradeoff

Physical-contact configurations can reduce an air interface but may transfer relative vibration motion into the soft polymer end surface. Historical observations documented contact-related damage after random-vibration exposure; they provide a mechanism of concern rather than a universal failure rate for every polymer fiber. [S4]

9.3 Inspection and maintenance

- Verify optical face geometry and surface cleanliness using qualified inspection methods.
- Record both initial IL and post-maintenance IL under consistent launch/reference conditions.
- Define repair and repolishing limits for the actual material and ferrule design.
- Treat debris as a system reliability issue involving connector access, cleaning tools and the alignment sleeve.

10. Random-mate loss, eccentricity and statistical manufacturing variation

For high-volume interconnect production, a critical design question is not simply whether a selected specimen mates with its own reference cable; it is whether independent assemblies across production lots and suppliers maintain an acceptable insertion-loss distribution when randomly cross-mated.

The historical POF avionics network engineering work repeatedly identified lateral optical-core misregistration as a major contributor relative to modest axial gap variation. In one analysis, the combined dimensional contributors were described as approaching about 95 µm of total offset capability. This theoretical data was backed up with exhaustive laboratory tests across a number of large OEM optics organizations with XiOptics providing products for evaluation. [S2, S3, S6]

10.1 First-order lateral core overlap

For two idealized, equally sized uniform step-index circular cores of radius r, the geometric overlap area at lateral displacement d ($0 \le d \le 2r$) is: $A_{overlap} = 2r^2 \arccos(d/2r) - (d/2)\sqrt{(4r^2 - d^2)}$. A simple coupling approximation is $\eta \approx A_{overlap}/(\pi r^2)$, giving $IL \approx -10\log10(\eta)$. Real POF coupling additionally depends on numerical aperture, refractive-index profile, launch distribution, gap and modal behavior; the formula is useful only for illustrating sensitivity.

10.2 Compensation and screening

Historical XiOptics ARINC 801 development documents describe hex-sector rotational registration relative to a master reference as a way to reduce the eccentricity component of random-mate IL. Earlier M29504 studies also discuss controlled selection/inspection methods matched to POF size variation. These historical methods demonstrate the need for manufacturing compensation but are not disclosed here as a production instruction. [S3, S4]

The design goal is a narrow, reproducible distribution of channel losses under true random mating—not a single favorable low-loss datum against a uniquely selected reference.

11. Development and test findings — documented historical evidence

The following results are supplied from project documents and test data. Dates, test populations, cable constructions and reference conditions varied. Accordingly, the entries are independent historical observations, not an from the aggregated qualification dataset.



Historical observation	Context / interpretation	Source
0.6 dB IL with ≤0.4 dB environmental variation	Historical design objective; not a measured performance distribution	S1 / S4
≤1.0 dB mated loss	Program-specific design/acceptance requirement	S2
~0.4 dB maximum on an tuned sets	Historical NXTCore POF test with specific end-face construction	S2
Some channels ~0.6 dB after ~100 maintenance cycles	Observed aging change in same development narrative	S2
0.3–1.7 dB range in separately evaluated large body of test samples	Untuned specimens; high-loss case associated with debris and damaged entry region	S2
After cleaning, some high-loss channels fell below 1.0 dB	Shows importance of contamination inspection; not proof of universal robustness	S2
20–80 µm noncontact end-face concepts	Design/test exploration, not current global tolerance used in production cable at XiOptics	S2 / S4

11.1 Interpretation of variability

The test record supports three conclusions: geometric compensation can reduce manufacturing-related loss variation; a controlled noncontacting interface can mitigate end-face wear; and foreign-object debris can create high observed loss even when the underlying terminus architecture is functional. Not every observed increase is therefore an intrinsic fiber/terminus design deficiency.

12. Environmental qualification and reliability framework

Qualification should be based on the end-to-end assembly: selected POF cable, production termination, ferrule/sleeve, connector insert, rear seals, backshell and harness routing. Historical program documents specified -55 °C to +100 °C continuous environmental design exposure for one proposed aircraft POF configuration. This was a requirement envelope that every current XiOptics POF configuration has been independently verified to. [S2]

Evaluation category	Principal failure modes to monitor	Required evidence
Thermal cycling / soak	Pistoning, axial gap drift, material aging, loss shift	IL vs. temperature, post-test retention/end-face inspection
Random vibration / shock	End-face wear, ferrule motion, contact chatter	In-situ IL; post-test microscopy and retention
Humidity / fluids	Polymer or jacket response, seal breach, corrosion	Application-specific materials and environmental reports
Mating durability	Wear, FOD, sleeve degradation, repeatability	Channel loss distribution by cycle and mating history
Cable pull / flex	Fiber shift, mechanical retention, bend loss	Force-displacement, optical stability and failure analysis
Random mate / cross supplier	Core offset, cavity true position, asymmetric sleeves	Production-lot paired matrix and statistical analysis

12.1 Qualification by similarity

Reuse of existing qualified GOF connector bodies and termini subassemblies lowers initial technical risk, but full equivalence cannot be presumed when the optical medium changes to polymer. Polymer behavior at the end face and cable attachment must be verified independently.

12.2 Evidence gap

The attached files document developmental test summaries, historical specifications and proposals. They do not provide a current, comprehensive, revision-controlled POF qualification report for every ARINC 801 and M29504 configuration

13. Application selection: ARINC 801 versus M29504 POF

Selection factor	ARINC 801 POF	M29504 POF
Primary use case	Dedicated ARINC 801 optical inserts and high-density systems	Existing size-16-compatible military and rectangular connector platforms
Terminus architecture	Keyed spring-carrier arrangement	Fixed pin and spring-loaded socket derivatives
Eccentricity management	Historically designed with rotational registration	Historically managed by cable/ferrule selection and inspection
Alignment element	Sleeve/insert may require POF-compatible configuration	M29504-specific hood/sleeve or connector arrangement
Integration burden	Check ferrule diameter against alignment sleeve	Check cavity true position and qualified connector sources
Cost / availability	Platform-dependent; possible dedicated insert cost	Often benefits from broad established connector market
Common dependency	Validated cable attachment/end-face process	Validated cable attachment/end-face process

13.1 Recommended selection sequence

- Define the optical link budget, wavelength, power, required data rate and total life cycle.
- Select and freeze the POF medium, core/cladding dimensions, jacket and strength-member construction.
- Identify the connector platform(s) and available cavity/insert geometry.
- Select a matching POF ferrule and alignment structure; do not assume GOF sleeves are compatible.
- Validate environmental loads, maintenance access and required random-mate yield.
- Request controlled XiOptics termination and complete assembly qualification documentation.

13.2 Supplied finished assemblies

Because XiOptics retains proprietary termination intellectual property, customers can procure controlled terminated termini and full cable assemblies rather than replicate the nearly decade long manufacturing process and test program. A commercial technical data package can provide outline geometry, connector compatibility, test conditions, acceptance data and recommended service instructions without disclosing the protected internal process.

14. Engineering conclusions

- POF performance in harsh environments is fundamentally a system-integration consideration. The polymer medium, cable architecture, retention system, ferrule, alignment sleeve, connector cavity and end face must be designed and validated together.
- Large core diameter makes POF relatively tolerant of some mechanical offsets but does not remove manufacturing-related random-mate loss variation, particularly in high-density connector networks.
- End-face durability and contamination control are critical to stable loss during shock, vibration and maintenance aging. Noncontacting end faces are a defensible option, provided the defined axial gap is maintained.
- XiOptics has developed POF-compatible products in ARINC 801 and M29504 formats and reports active application of its M29504 POF products in aerospace and space programs. Application-specific qualification and configuration records remain the controlling evidence.
- Customers do not need access to proprietary XiOptics cable termination recipes to evaluate finished assemblies. Controlled product data, representative samples and verified system tests can establish engineering suitability.

15. References and source characterization

S1. XiOptics, Plastic Optical Fiber Termini and Connector Solutions, POFAN historical presentation, POF Symposium.

S2. Section C Technical, NXTCore POF ARINC 801 Termini and Alignment Sleeves, historical RFP technical response to Avionics POF program consortium.

S3. RFP Response Overview, NXTCore POF ARINC 801 program briefing POF Symposium.

S4. XiOptics, 2nd RFI Summary Response, April 12, 2012, POFAN (supplied source; proprietary).

S5. XiOptics, Commercial Aircraft POF Consortium, POFAN development submittal.

S6. Yasuhiro Koike, Recent Status of High-Speed and Low Loss POF, Keio University, June 14, 2000.

S7. XiOptics, POFAN November 21, 2011 presentation (supplied source; proprietary).

Technical and disclosure notice

The references above are included to support traceability. Some original documents contain confidentiality/export-control notices and third-party proprietary legends. This standalone white paper intentionally summarizes only high-level engineering principles and selected historical outcomes.