Aerospace Fibers
“Lessons Learned”

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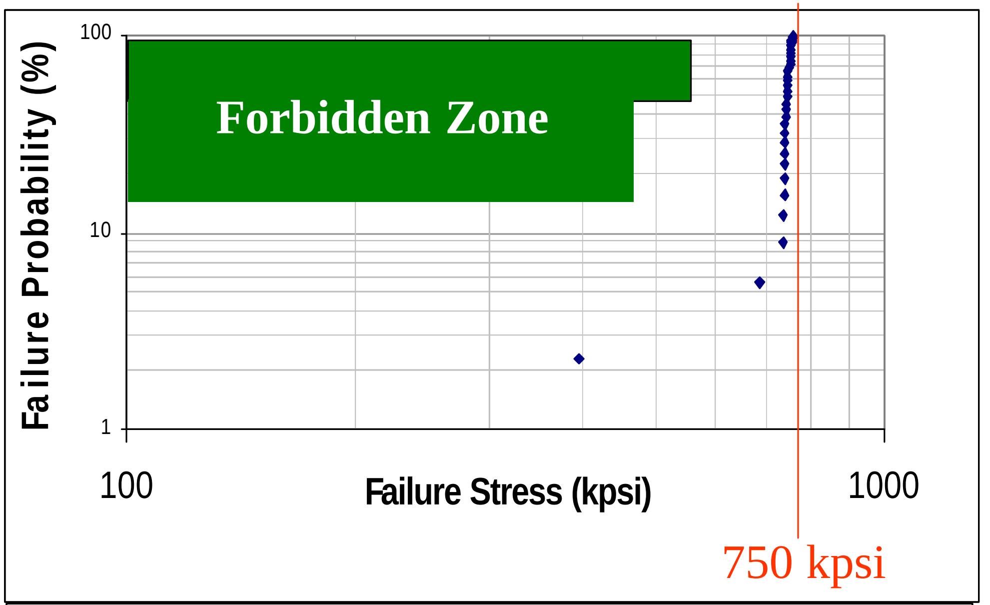
October ‘05

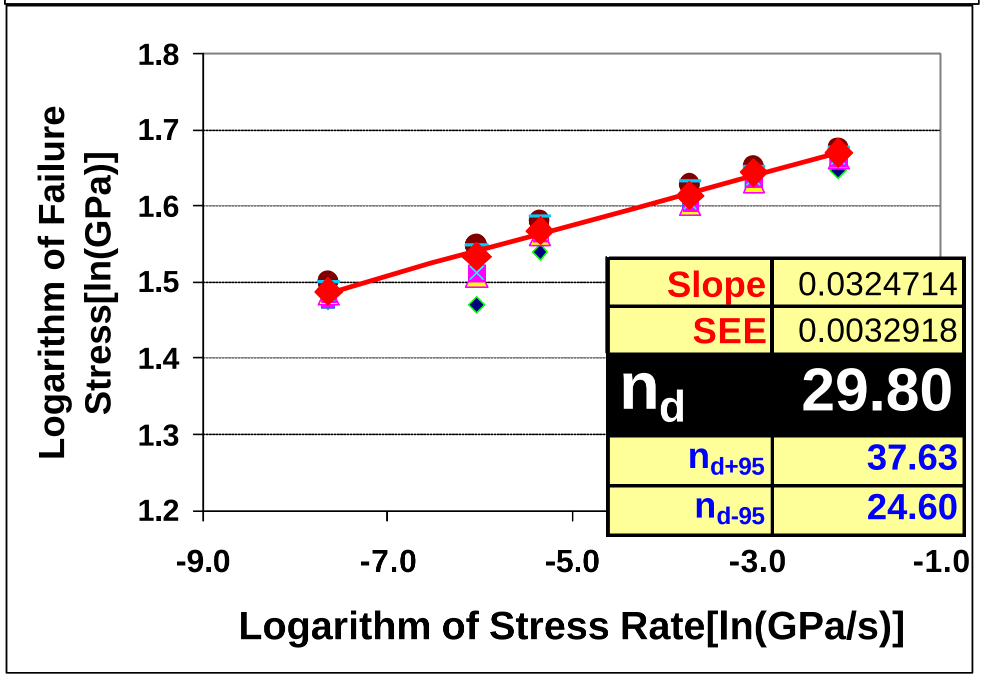
Our Mission

Nufern designs, manufactures, sells, and supports lot-controlled specialty fibers, optical fiber laser and amplifier products for leading edge technology applications.

Nufern Advantage: Better Fiber Performance

- Telcordia GR 20 type testing:
  - High strength, near theoretical limit.
  - High fatigue failure resistance. Best in the world.
  - Enable the highest power integral fiber lasers to date.
- Cost 218 Model indicates 10^7 year life expectancy.

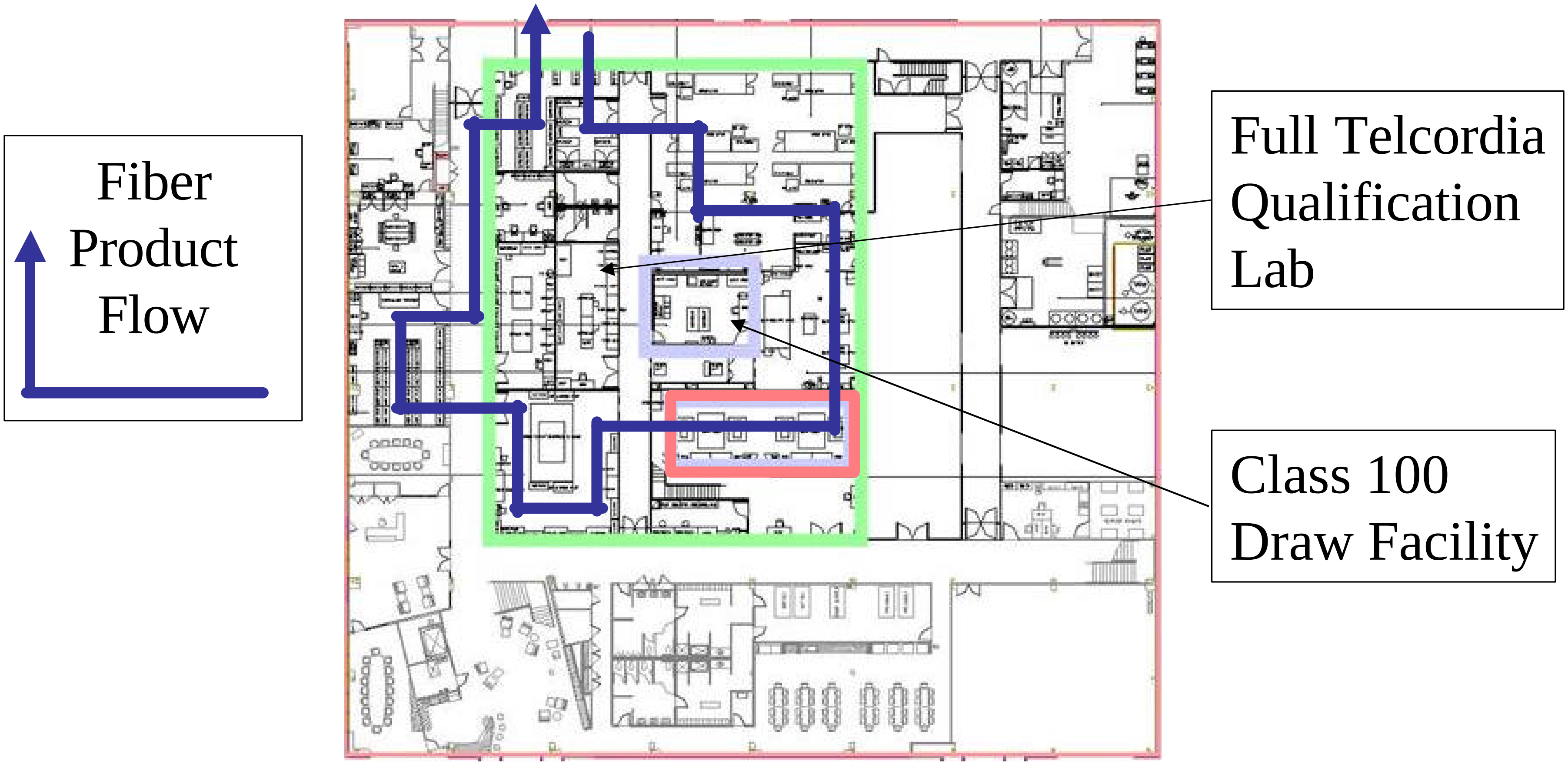




Slope	0.0324714
SEE	0.0032918
n_d	29.80
n_{d+95}	37.63
n_{d-95}	24.60

Custom Clean / Lean Manufacturing Space

(Designed for lowest cost, highest yield, in mid volumes)



Experience Determination

www.nufern.com

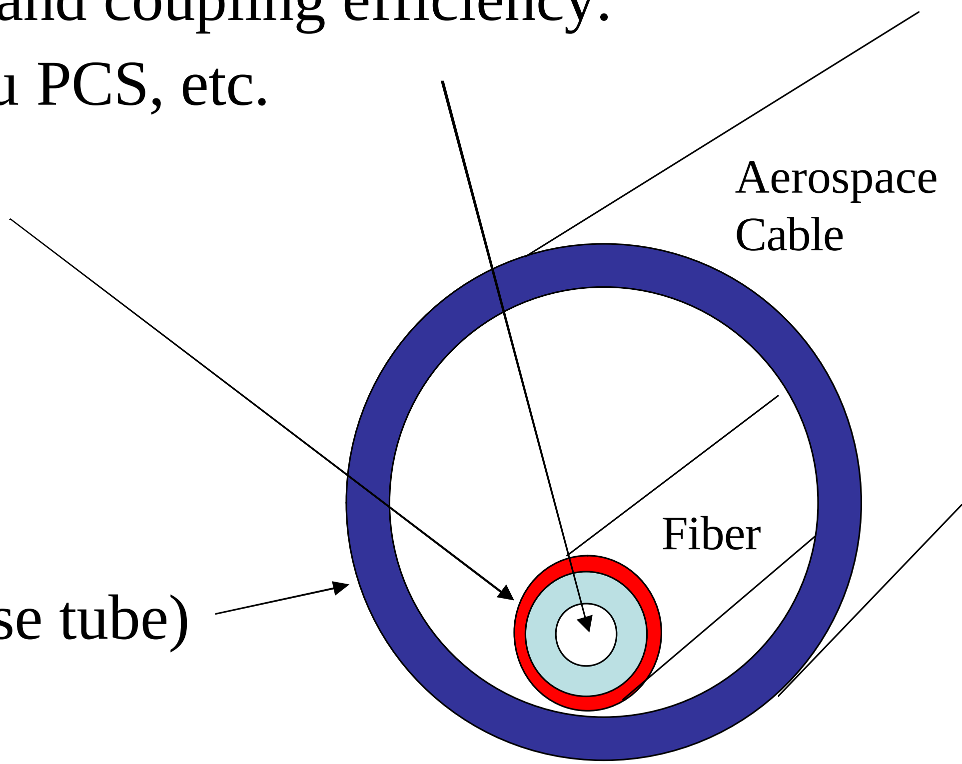
NUFERN Driven To Light.

Aerospace Fibers

- Difficult Application:
  - High and wide temperature range.
  - No emissions wanted in spite of operation in "near vacuum".
  - Resistance to radiation of all types and magnitudes.
  - Resistance to chemicals; ie salt water and organic solvents.
  - High resistance to, and near zero emissions when burned.
  - Tolerance for high cyclical stress, shock and vibration.
  - Tolerance to unfavorable installation techniques.
- Need to be connectorized for maintenance purposes.
  - Fusion splicing & recoating fiber on an aerospace vehicle is impractical.

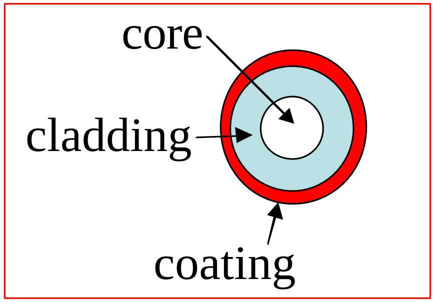
Aerospace Fiber Solutions

- Waveguide:
  - Multimode (graded and stepped index) used to maximize core diameter and coupling efficiency.
  - 50/125µ, 100/140µ, 200µ PCS, etc.
- Coating materials:
  - Polyimide
  - Silicone
  - Acrylate
- Cable structures:
  - Loose Tube (or semi loose tube)
  - Tight buffer



Waveguide design

- Early systems had low brightness T_x devices.
- Early systems had low bandwidth and insensitive R_x devices.
- Couplers were retrofit into existing electrical connector designs.
- This dictated:
  - Large cores ~ 200µm for maximum target area.
  - Highest NA ~ 0.375 for maximum light capture.
  - Custom connectors were developed and implemented.
  - Low bandwidth. (Max 10MHz/km)



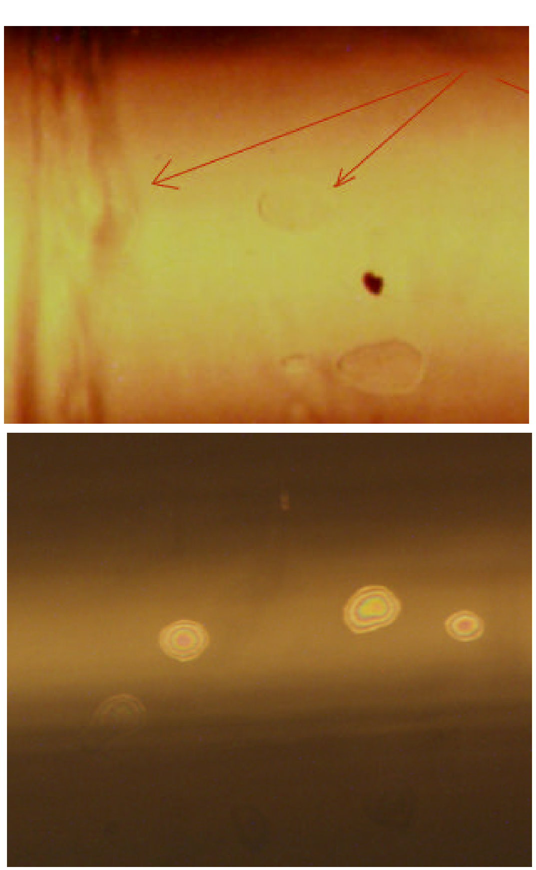
- The large core polymer clad designs were unreliable.
- The telecom industry has generated a great deal of standard 125µm robust low cost, high bandwidth connector hardware.
  - Cost / benefit analysis suggests a move in this direction.

Waveguide Issues

- Large core fibers ~ 200µ have inadequate BW for today's needs. (< 10MHz km)
- Thin Polymer Clad Fibers (PCS, HCS, etc.) suffer from long term reliability issues, particularly if delivering power.
- Crimp & Cleave terminations for PCS fibers exhibit high variability and reduce available BW.
- Installation & service methodologies designed to minimize microbend stress on fiber are not followed.
- Maintenance of large diameter FC (face contact) connectors is tedious and not followed.
- Some designs suffered premature failure. (Carbon coatings prone to ESD failures)

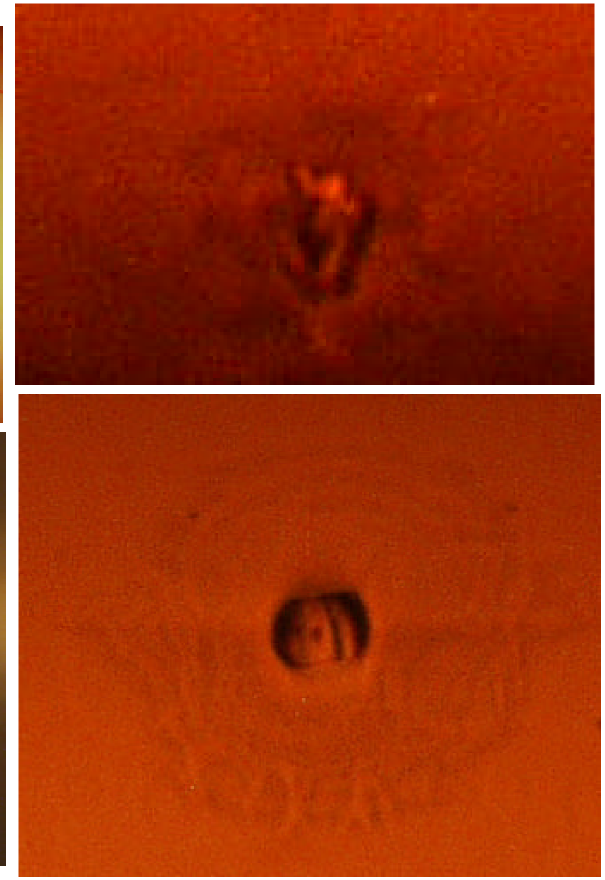
Hard "Polymer Clad" Fiber Defects

Hard thin (<5µM) cladding tends to delaminate from the glass. It requires a "permanently shrinking" coating (Tefzel™) to stay intact.



Delamination

Extruded Tefzel™ on thin clad deposits hard contaminants into the cladding causing point sources of failure

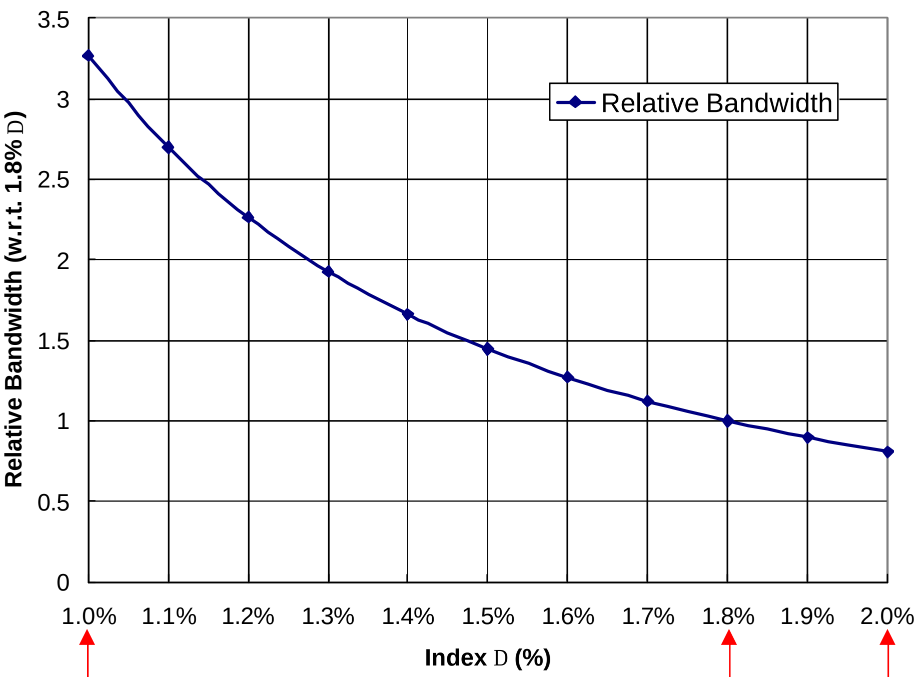


Contamination

Result: Almost all current systems use glass clad fibers

All Glass Waveguide Trade Off

Relative Bandwidth

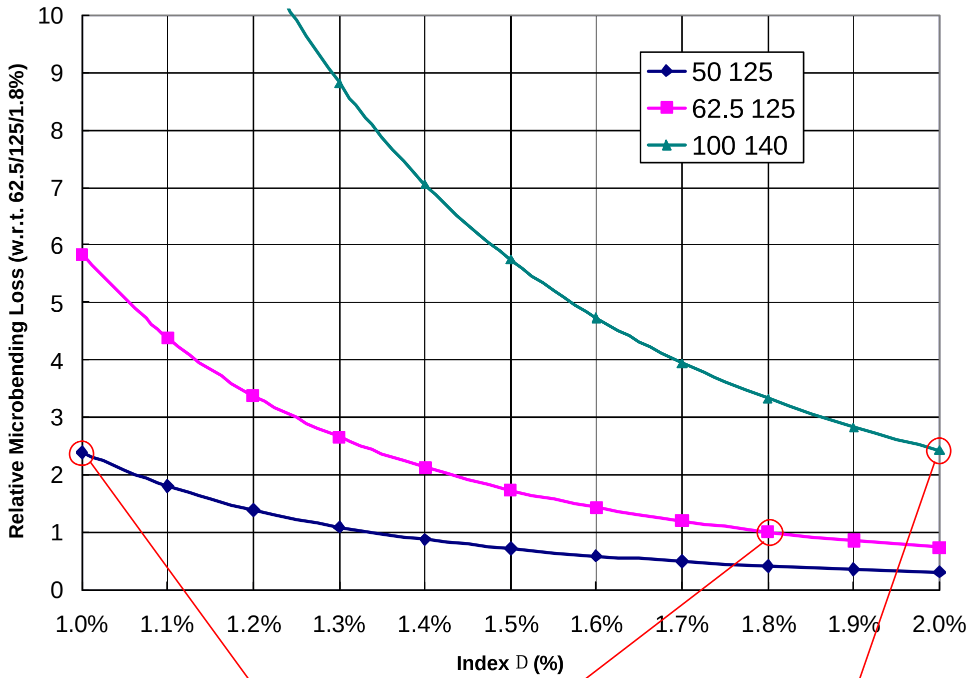


50/125µ
0.22 NA

62.5/125µ
0.275 NA

100/140µ
0.29NA

Micro bend Loss



50/125µ

62.5/125µ

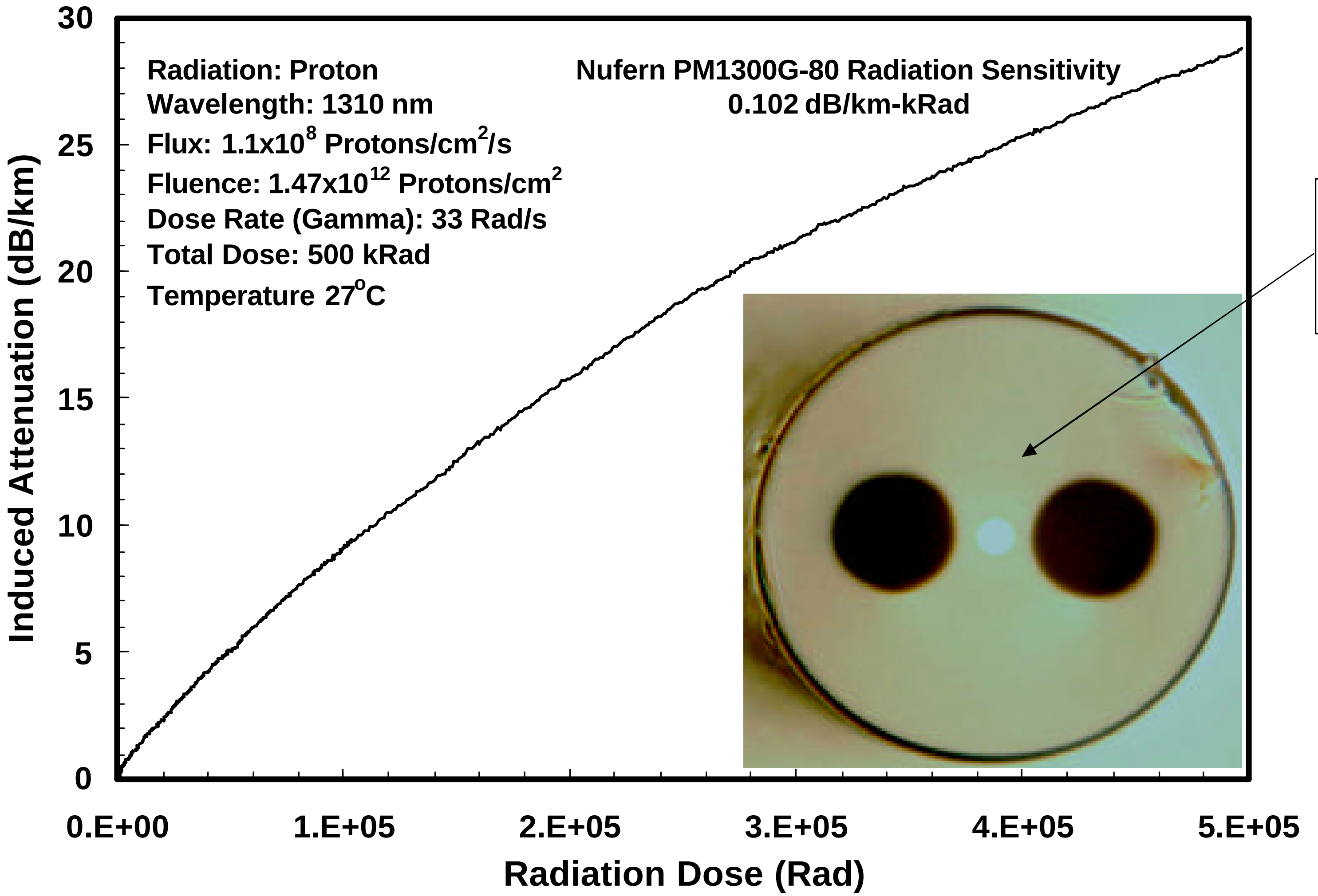
100/140µ

- Core Ø↓ & NA↓ => Bandwidth↑ & Bend sensitivity↑
- Core Ø / Clad Ø ratio↓ => Bend sensitivity↑

“Ultimate” aerospace waveguide…

- Glass core & Glass cladding structure (reliability).
- Smallest core (maximum bandwidth)
- Highest possible Core Ø/Clad Ø ratio (bend insensitivity)
- Largest possible NA (highest tolerance to connector misalignment)
- 125µ outside diameter to utilize telecom hardware. (minimize cost, maximize connector selection)

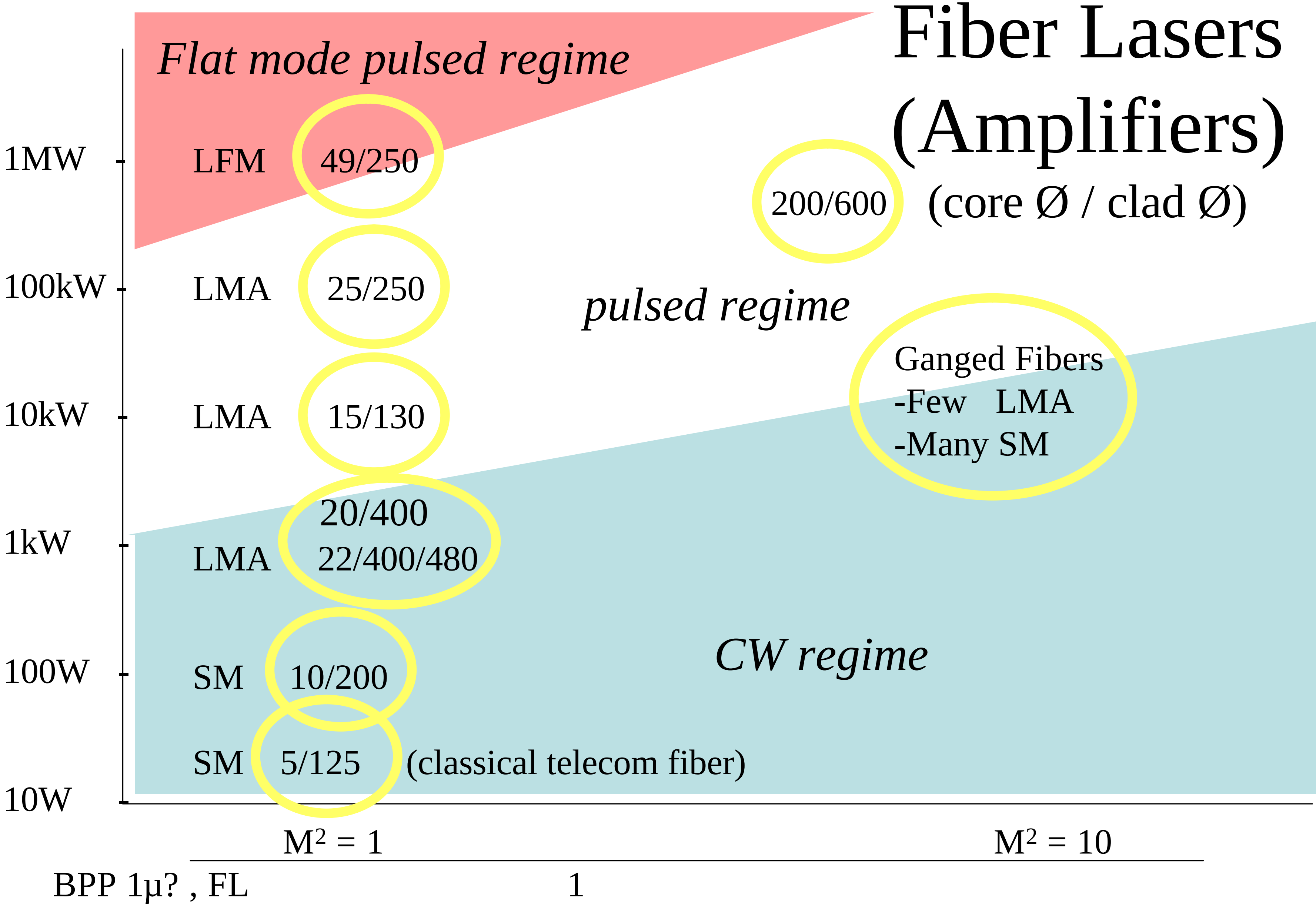
High Inherent Radiation Tolerant Fibers



Panda construction

Data:
Light Ion
Radiation Lab
Berkley CA
Joe Frieble

Fiber Lasers (Amplifiers)



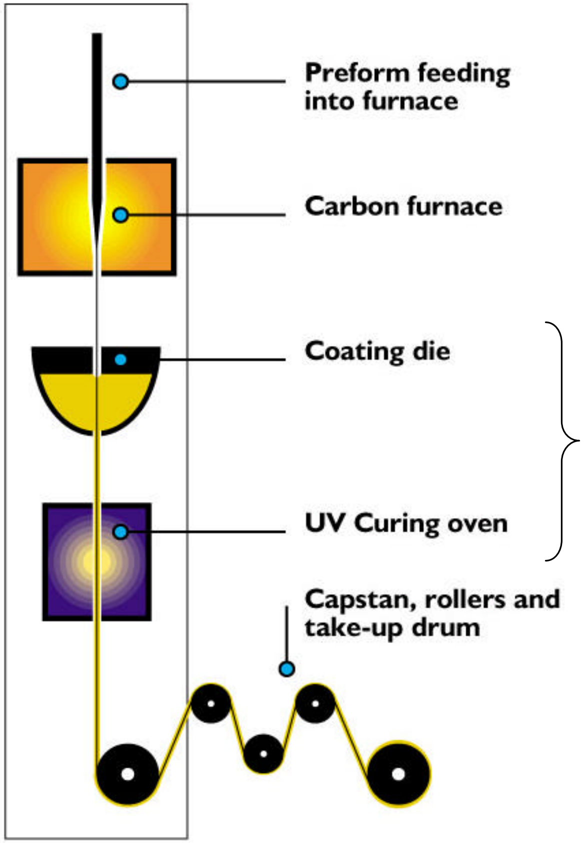
Coating Design

- Fiber coating serves two functions:
  - Protect fiber from chemical attack. (Water most prevalent)
  - Protect fiber from microbend stresses.
- Many materials and combinations have been tried.
- Full qualification is expensive and time consuming, as a result some fiber coatings that are essentially experimental have made it into flight hardware because of need and time constraints.

Acrylate Coatings

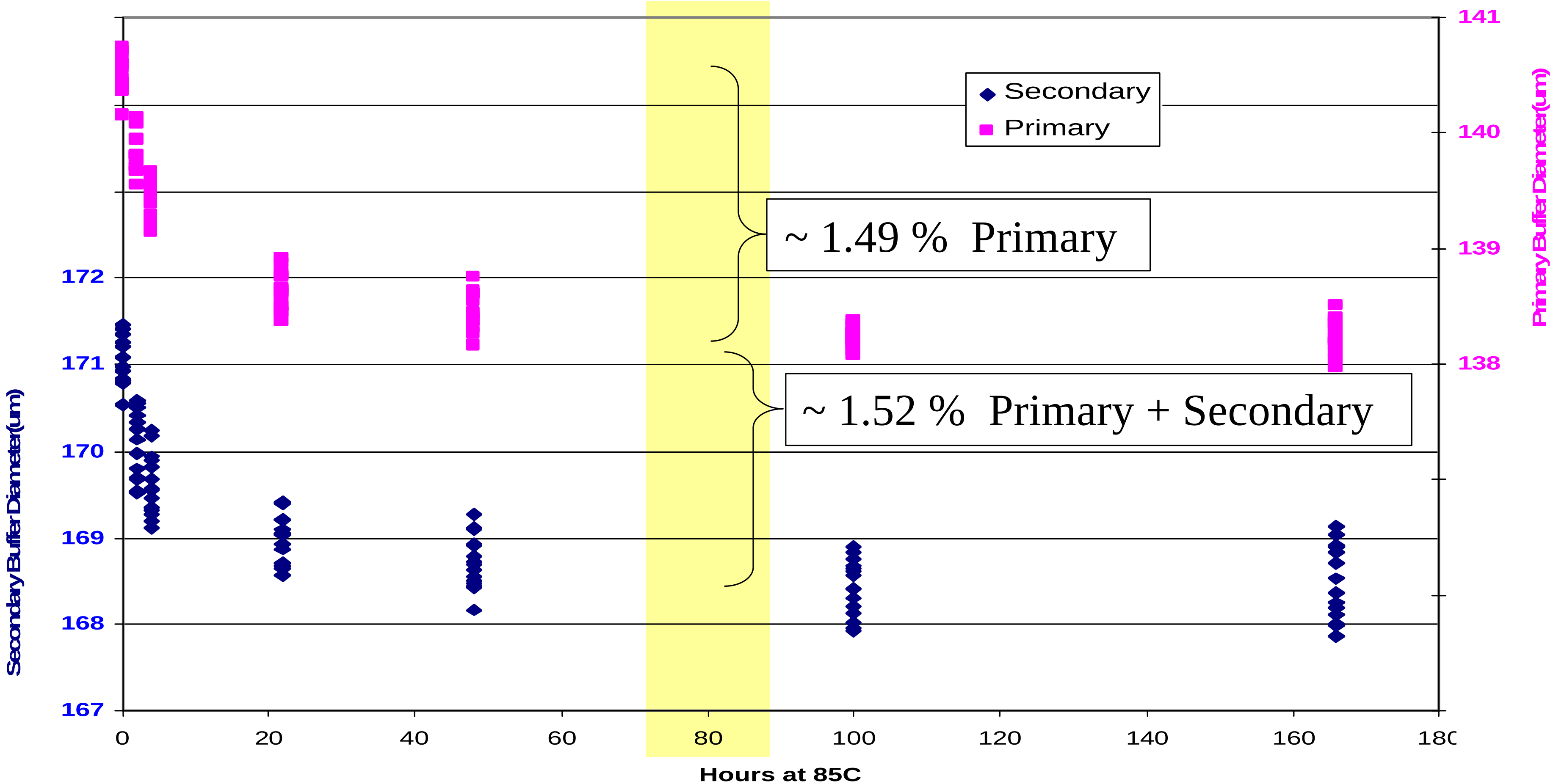
- Were developed for the telecom industry 20 years ago.
  - New materials with OI temperatures of > 200ºC are rated from -55ºC to +125ºC with excursions to +180ºC for several 10s of hours.
  - Old acrylates (pre 2002) were maximum rated for –5ºC to +85ºC.
  - Typically applied as a dual coating, the inner a soft high RI material to protect from microbend forces and absorb leaked core light. The outer layer is hard to provide abrasion resistance and minimize friction.
- Do not perform well when attacked by common organic solvents, and in extreme thermal environments.
- Have proven themselves durable and practical when used as designed.
  - Provide excellent protection from nicks, bends and moisture.
  - Are easily stripped clean for termination.
  - Are telcordia qualified for 22 years service life.
  - Have an enormous deployment record.

Acrylate Coated Fiber Drawing



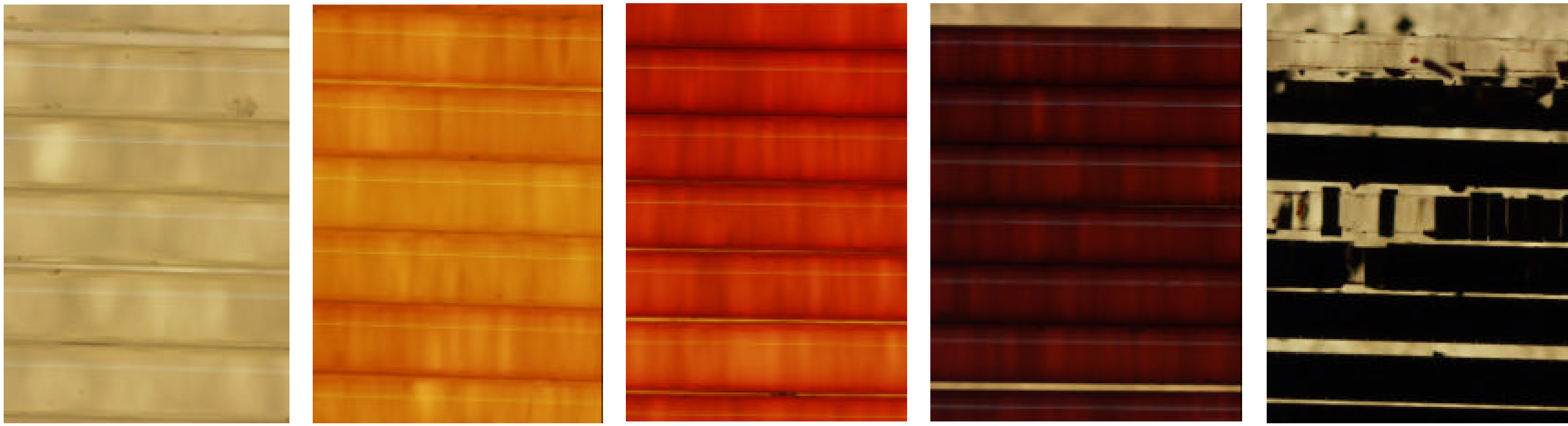
Repeated for multi – coat applications

Acrylate (polymer) coatings shrink



Result: Critical applications requiring precision winding or fiber bonding specify thermal post processing.

Acrylate Coating Life Cycle



As Built	After 1 year (acc.)	After < 5 years (acc.)	After < 22 years (acc.)	After 100 Days @ 175° C (Nearly black, Crumbling)

Orange / Brown color

Test using Nufern HTA using dual coat Acrylate with OI temperature > 200°C

Silicone Coatings

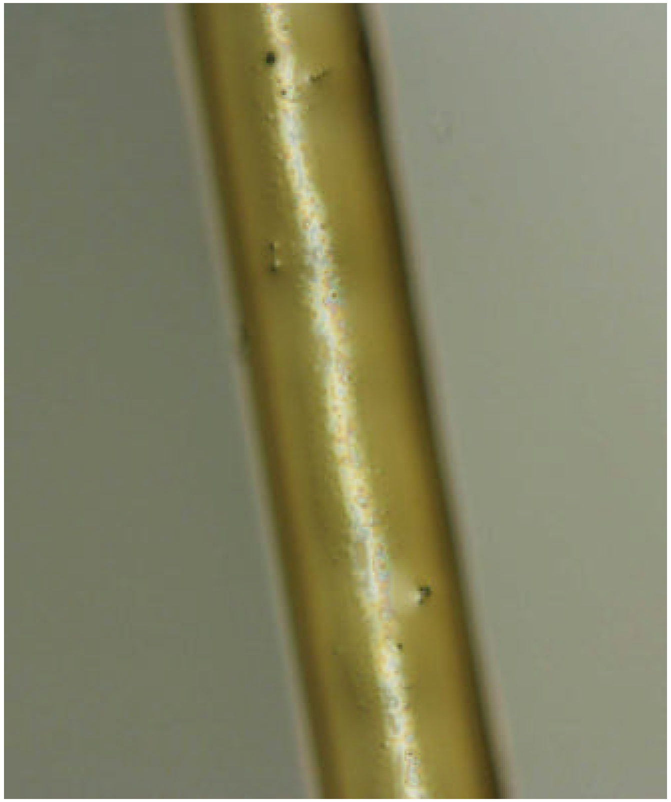
- Provide a good fiber coating for a modestly higher temperature range. Typically -25º C to +150º C.
  - Low RI silicones return escaped core light to the cladding so are preferred in some power delivery applications.
  - Show good resistance to many common solvents.
- Present known challenges for the fiber manufacturer, the cable assembler, and the ultimate users:
  - It is very difficult to clean a stripped fiber thoroughly.
  - Most bonding agents are effectively released by silicones.
  - Silicone continues to outgas for the life of the application. It therefore looses mass and volume over time.
- Silicones generally perform as advertised, and have a significant installed base in many harsh environments.

Polyimide Coatings

- Are hard and durable, with high and wide operating temperature ranges. Typically -65º C to ~ +300º C.
- Fibers are coated with multiple thin layers to ~ 20µm.
- Contain ~ 4% water by volume when fully cured.
- Exhibit low friction so can not be proof tested conventionally.
- Are highly tolerant to most solvents.
- Are stripped by immersion in hot (> 100°C) conc. H_2SO_4.
- Most problems with PI fibers are as a result of improper curing or poor storage & post processing.
- Are sometimes used effectively in combination with Carbon (hermetic) coatings.

Polyimide (PI) Coating Failures

Typical "under curing"
(post application reflow)

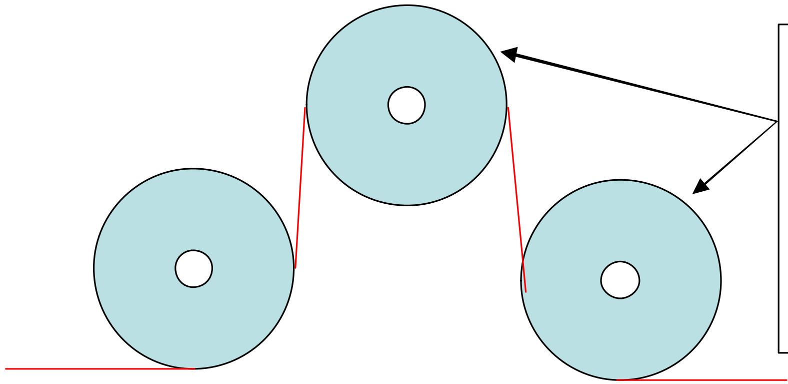


Typical "blistering"
(inadequate cure between coats)

PI Coating Application Guidelines:

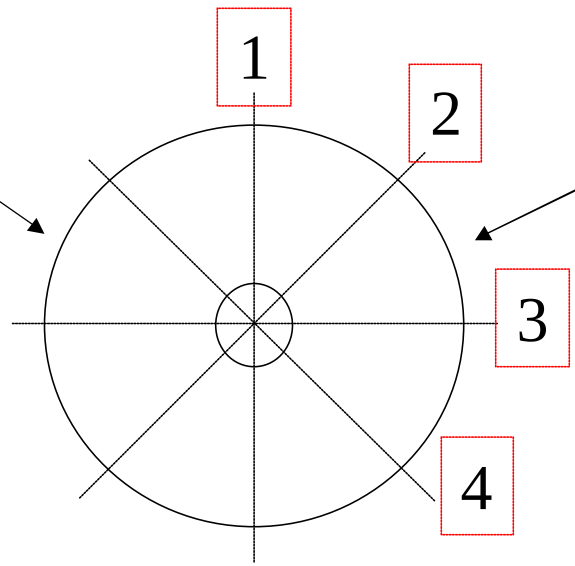
- A 20µm coating on fiber takes ~ 1Hr at elevated temperature to fully cure.
- Drawing layers too quickly (inadequate cure) causes subsequent layer bubbling and allows fiber to move.
- Finished fiber must be stored dry.
- Fiber requires an elevated temperature drying cycle prior to cabling. (entrained moisture flashes to steam)
- Cable materials must be extremely dry before used in cable making process.

Proof Testing Polyimide Coatings



Fiber is drawn through sets of fixed wheels of specified diameter to impart a bending (tensile) stress on the outer surface of the fiber.

Fiber cross section



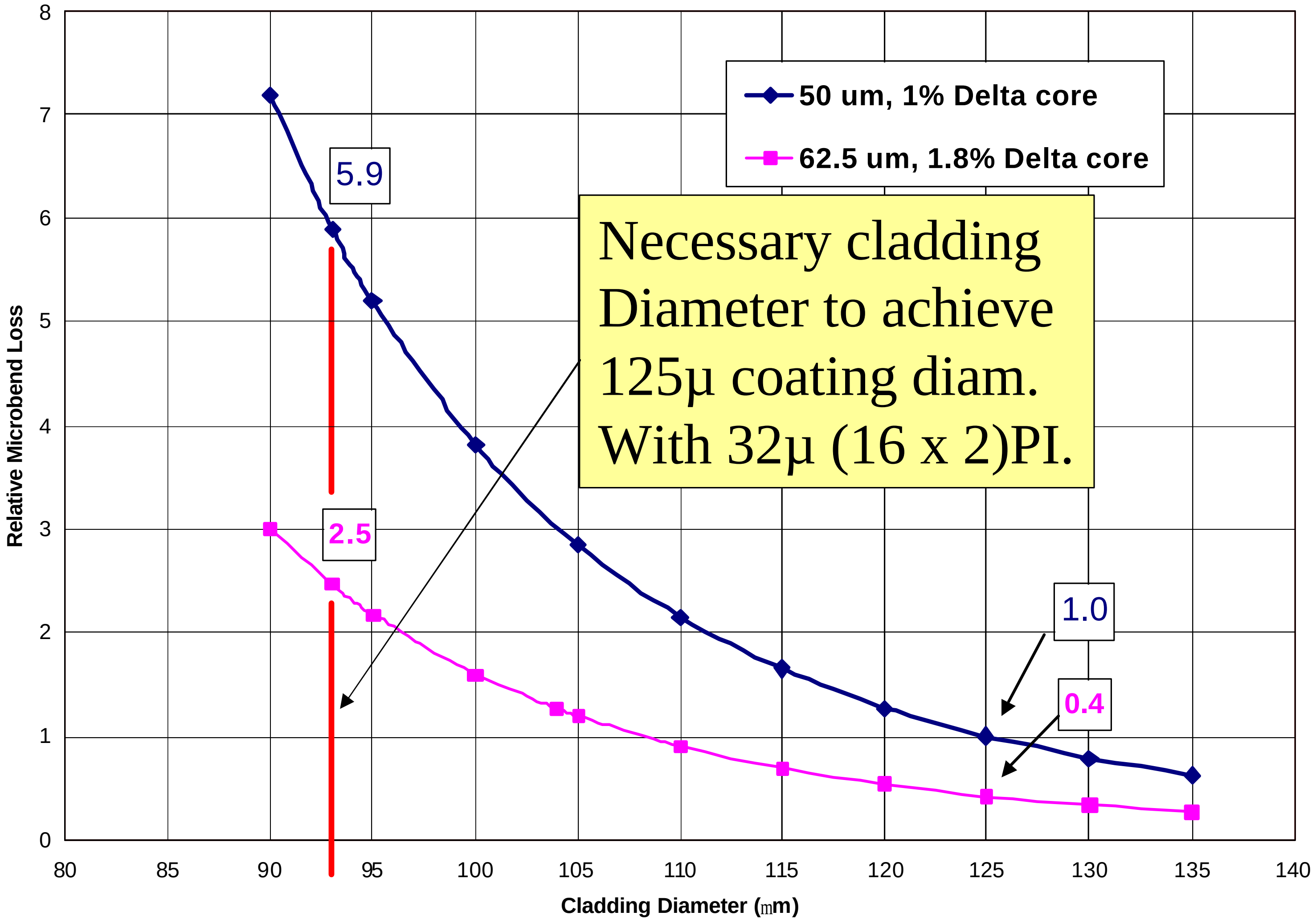
Fiber is drawn through 4 sets of Wheels, each at 45° from the others

Clever Alternatives to Stripping PI

1. Terminate in custom large diameter ferrules with intact PI coating.
2. Terminate in standard telecom. ferrules with intact PI coating (suffer some bend loss due to core Ø / clad Ø ratio)

- Because PI coating is relatively thin concentricity error and the resulting error in connector alignment can be managed during the coating process.

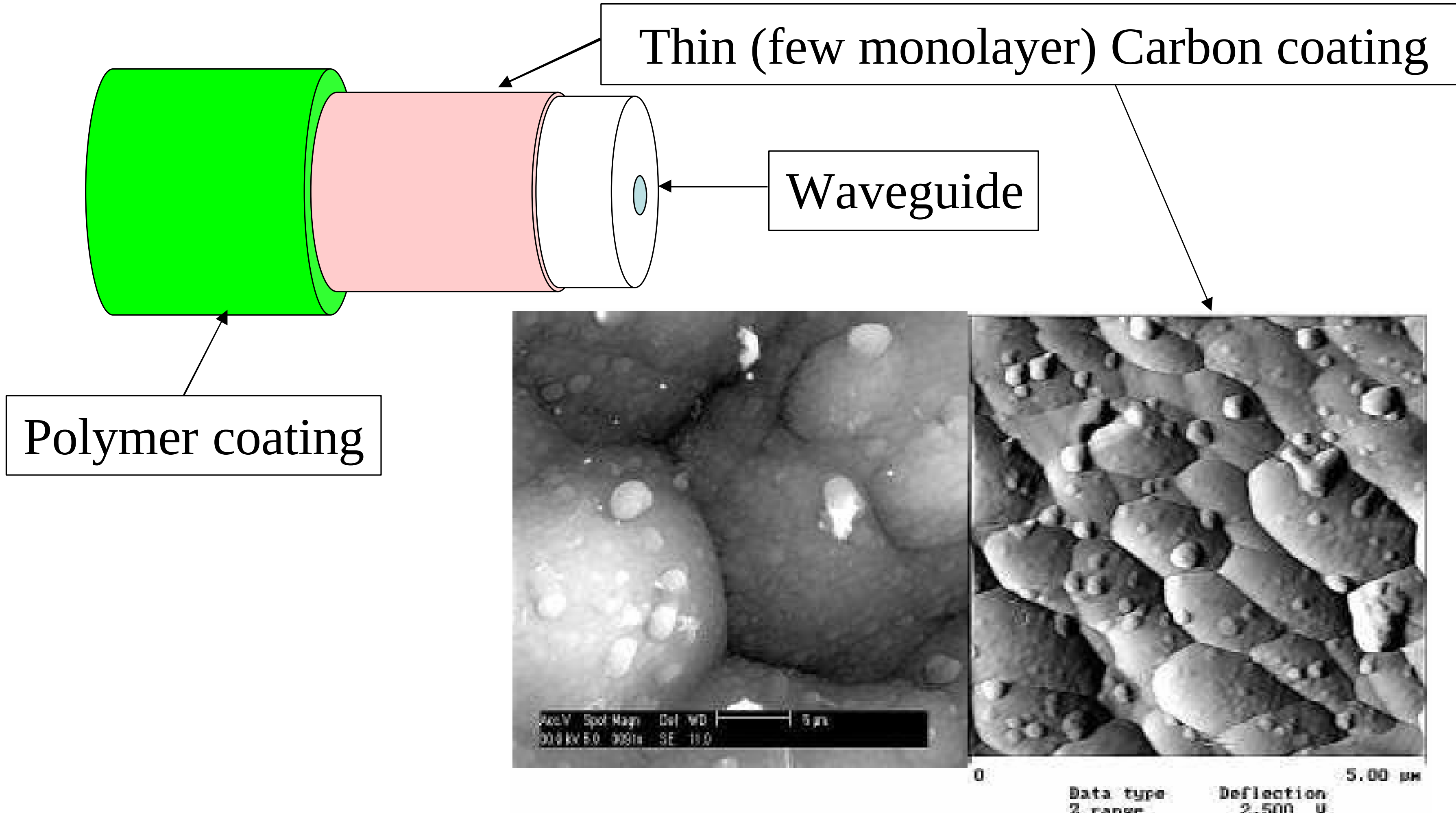
Micro Bend Loss for 125µ "No Strip" PI



Atomic “Carbon” Coatings

- Can provide an effective hermetic seal against water or H_2 gas ingression.
- Reduce the raw tensile strength by about $1/5^{th}$ but provide a >5X stress corrosion failure (n) rating increase.
- n values in excess of 100 are possible (common).
- Carbon is a semiconductor and the resulting fiber is ESD Sensitive. (NOT USUALLY ANTICIPATED)
- Care must be taken to account for ESD sensitivity during all steps of manufacture & deployment.
- Finished products have been shown to be robust.

Carbon Coatings



SEM STM

Aerospace Cable Construction

- Loose Tube
  - Largest operating temperature range
  - Least negative effect in high transient temperature conditions.
  - Difficult to terminate short lengths < 2m. Excess fiber spirals in tube.
  - Cable is somewhat bulky and subject to kinking.
- Tight Buffer
  - Easiest to terminate
  - Smallest dimensionally so gives highest bandwidth/size.
  - Has difficulty meeting low operating temperature requirements.

Conclusions

- Waveguides have migrated to "all glass" constructions.
  - Debate continues on "standards".
- 3 polymers are variously used. Acrylates are increasingly used "in cabin".
  - High desire for a strippable polyimide.
- Carbon coatings are falling from favor because of ESD sensitivity.
  - High desire for a non conductive atomic hermetic coating.
- Both cable constructions are in common use.

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