Best Practices for Manufacturing, Designing, and Applying EHV Polymer Insulators

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Abstract:

Polymer insulators have gained widespread acceptance in transmission applications up to 230kV, with mixed performance outcomes. These results have often been influenced by inadequate design practices, improper application, and limited understanding of polymer material behavior. Despite these early challenges, advancements in polymer technology and application engineering have demonstrated that, when properly designed and applied, polymer insulators can deliver reliable long-term performance and cost-effective solutions at Extra High Voltage (EHV) levels, including 500kV and 765kV systems. This paper explores the evolution of polymer insulator technology and outlines key considerations for successful implementation in EHV transmission networks.

Historical Background:

Polymer insulation technology was initially developed in the mid-1940’s for indoor electrical applications. These early polymer insulators, while effective in controlled environments, encountered significant performance challenges when exposed to outdoor conditions such as UV radiation, moisture, and pollution. Through iterative development and field testing, the first successful outdoor applications emerged in the early 1960’s, primarily on distribution lines.

By the 1970’s, polymer insulators had evolved sufficiently to be deployed in outdoor transmission systems. The first-generation polymer insulators introduced in the 1980’s were typically specialty designs, targeted for use in environments where traditional ceramic insulators exhibited performance limitations, particularly in areas with high contamination or severe weathering. Vandalism was also a key factor in the early adoption of polymer technology. These early designs laid the groundwork for the advanced polymer technologies in use today.

Introduction:

The development of first-generation polymer insulators marked a significant shift in transmission line technology, though it was accompanied by a steep learning curve. These early designs were heavily influenced by the principles and practices established for ceramic disc insulators, which limited their initial performance and reliability. Despite these challenges, certain first-generation polymer insulators demonstrated robust performance, including successful applications at Extra High Voltage (EHV) levels.

Over the past three decades, substantial advancements have been made in polymer materials, housing application, seal reliability, and manufacturing efficiencies. These improvements have led to enhanced mechanical strength, superior hydrophobicity, improved resistance to environmental degradation, and longer service life. This paper examines the evolution of polymer insulator technology, with a focus on the critical innovations that have enabled reliable performance in EHV applications. It also provides guidance on how these technological enhancements can be effectively integrated into modern EHV system designs.

1. Knowledge Gaps and Design Limitations

The initial development of polymer insulators was hindered by a limited understanding of polymer behavior in high-voltage outdoor environments. Early designs were heavily influenced by ceramic insulator design and standards, which did not translate effectively to polymer insulators. While both materials serve as insulators, they exhibit fundamentally different mechanical, electrical, and aging characteristics. This variance led to less effective performance and a steep industry-wide learning curve for both suppliers and users.

Fig. 1: Ceramic Technology used to develop 1st Generation Polymer

2. Material and Manufacturing Challenges

Early polymer insulators utilized a variety of housing materials, including:

- EPDM (Ethylene Propylene Diene Monomer)
- Silicone Rubber (HTV & LSR)
- Material Alloys and Blends

Housing application methods varied and included molded, extruded, and slip-on techniques. Notably, bonding between the housing and the fiberglass core rod was not initially required, which contributed to moisture ingress and interface degradation.

Other key characteristics of early designs included:

- Sheath Thickness: early generation designs used 1.5mm sheath thickness.
- Use of standard E-glass rods containing boron oxide, which are susceptible to brittle-fracture (BF) under stress corrosion.
- Wedge - epoxy-potted end fitting attachment lacked mechanical strength and reliability.
- Minimal or no sealing at interfaces, increasing vulnerability to environmental contamination and moisture penetration.

3. Application-Specific Limitations

When applied in the field, early polymer insulators were often used as direct section length replacements for ceramic strings. This approach resulted in under-insulation, which led to performance issues:

- **Reduced dry arc distance**: Typically, 15–20% shorter than equivalent ceramic strings, often resulting in two to three fewer discs of insulation.

- **Leakage distance**: Often equal to or less than that of ceramic equivalents, limiting performance in polluted environments.

- **Corona Protection**: Rarely applied in early designs (less than 345kV) due to limited understanding of its impact; lack of grading devices led to localized electric field stress, accelerating material degradation and failure.

- **Brittle fracture**: The most common historical failure mode of polymer insulators, due to stress corrosion of the fiberglass core and inadequate sealing.

Polymer Technology Advancements (1980's–2025)

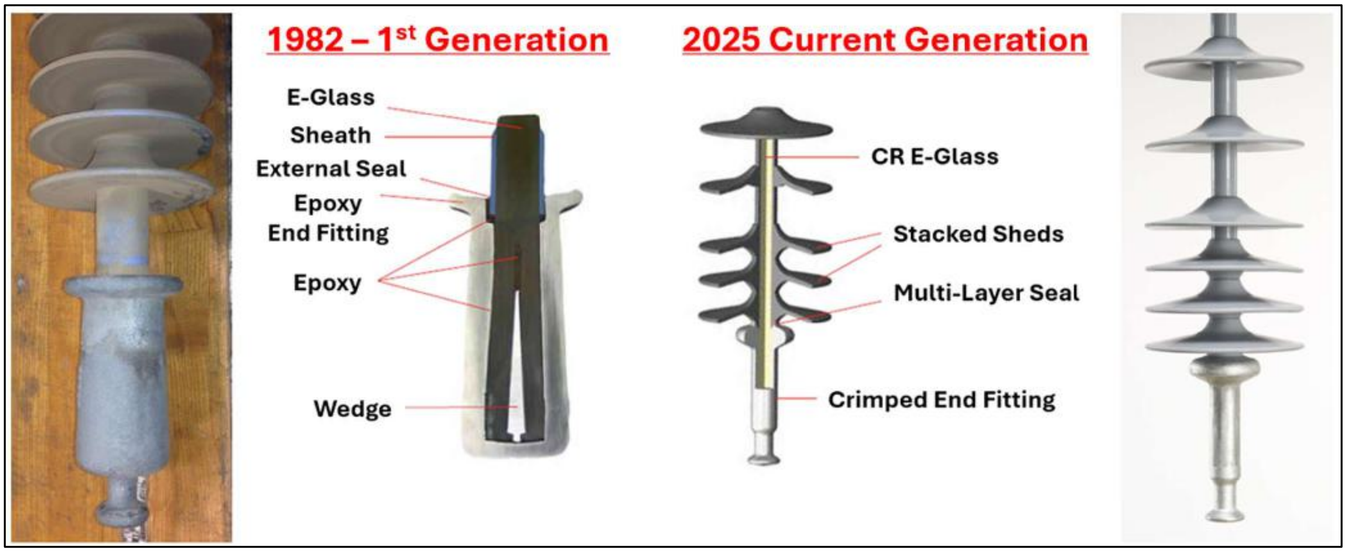


Fig. 2: Polymer Evolution – Then & Now

Housing Material:

- Early Generation silicone rubber insulators out-performed other materials.
- EPDM and alloy blends transitioned to silicone rubber.
- HTV Silicone becomes the industry standard for its hydrophobicity, resistance to UV and superior performance in the harshest environments.
- Silicone Formulation Matters: Not all silicone materials are equal; performance depends heavily on the silicone composition.

Benefits of Silicone in Polymer Insulators

- Hydrophobicity: Naturally repels water, reducing surface leakage currents.
- Hydrophobic Recovery: Regains water-repelling properties after an electrical event.
- Encapsulation of Contaminants: Prevents conductive paths from forming on the surface, encapsulating contamination and preventing it from wetting out.
- Thermal Stability: Performs reliably across a wide temperature range.
- Flame Retardant: Inherently resistant to ignition and combustion.
- Corrosion & Weathering Resistance: Withstands UV, tracking & erosion, and harsh environments.
- Inorganic (Si-O) Backbone: Provides superior chemical and thermal durability.

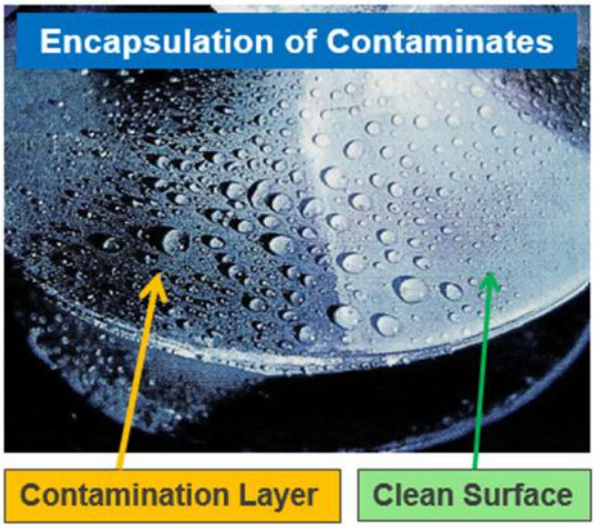
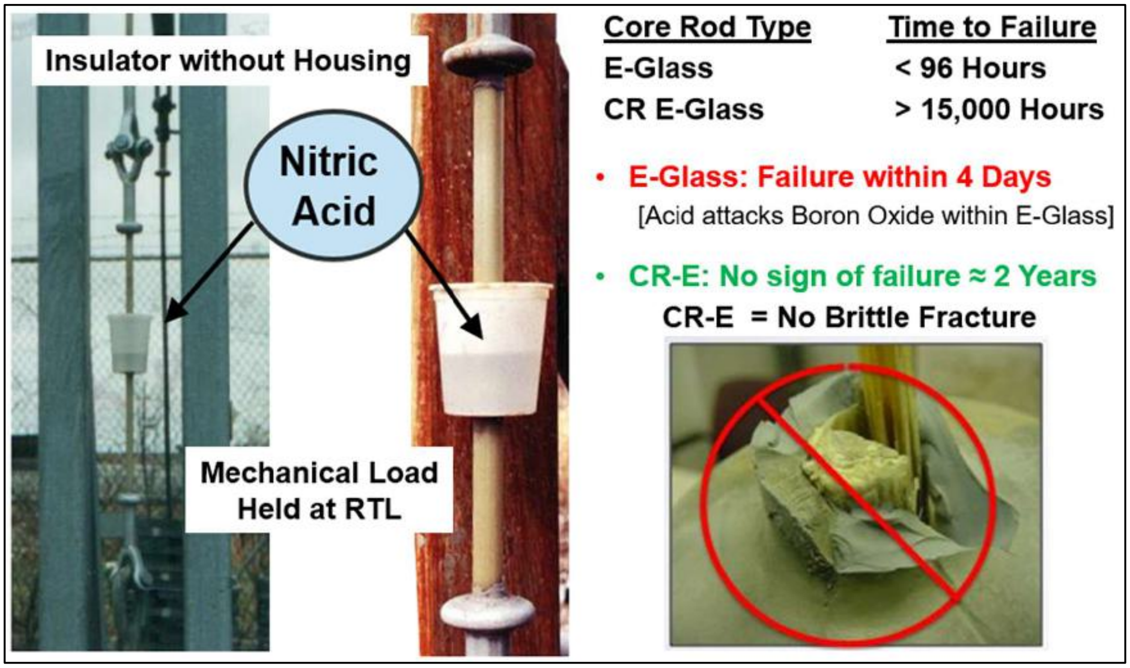


Fig. 3: Benefits of Silicone

Core Rod:

- Upgraded from standard E-glass to corrosion-resistant (boron free) E-glass (CR-E).
- Eliminating the risk of brittle fracture.



Core Rod Type	Time to Failure
E-Glass	< 96 Hours
CR E-Glass	> 15,000 Hours

- E-Glass: Failure within 4 Days [Acid attacks Boron Oxide within E-Glass]
- CR-E: No sign of failure ≈ 2 Years CR-E = No Brittle Fracture

Fig. 4: CR-E Glass Acid Test

End Fitting Attachment:

- Shifted from epoxy potting to controlled compression (crimping) methods, improving mechanical reliability and consistency.
- End fitting designs evolved to use stronger, lighter materials with improved mechanical strength and reliability.
- Crimping Process Improvement: Modern crimping methods are engineered to prevent rod cracking at the source, replacing earlier reliance on acoustic emission testing, which only detected cracks after they occurred.

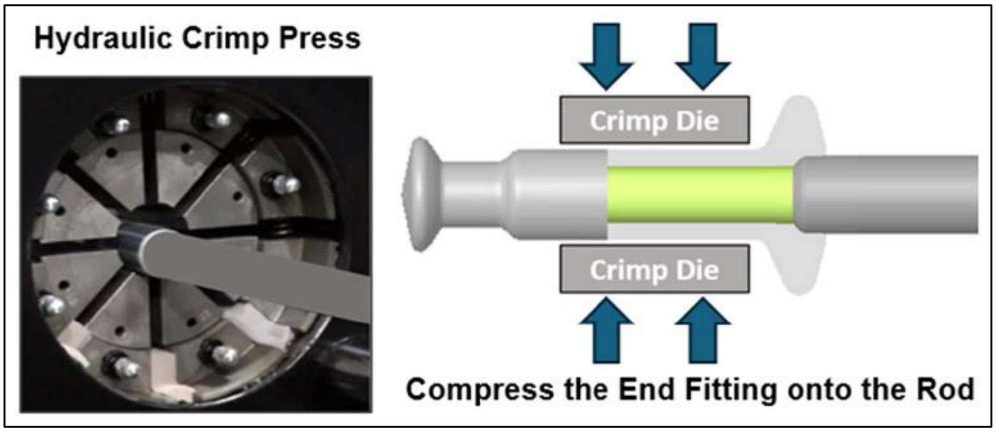


Fig. 5: End Fitting Attachment

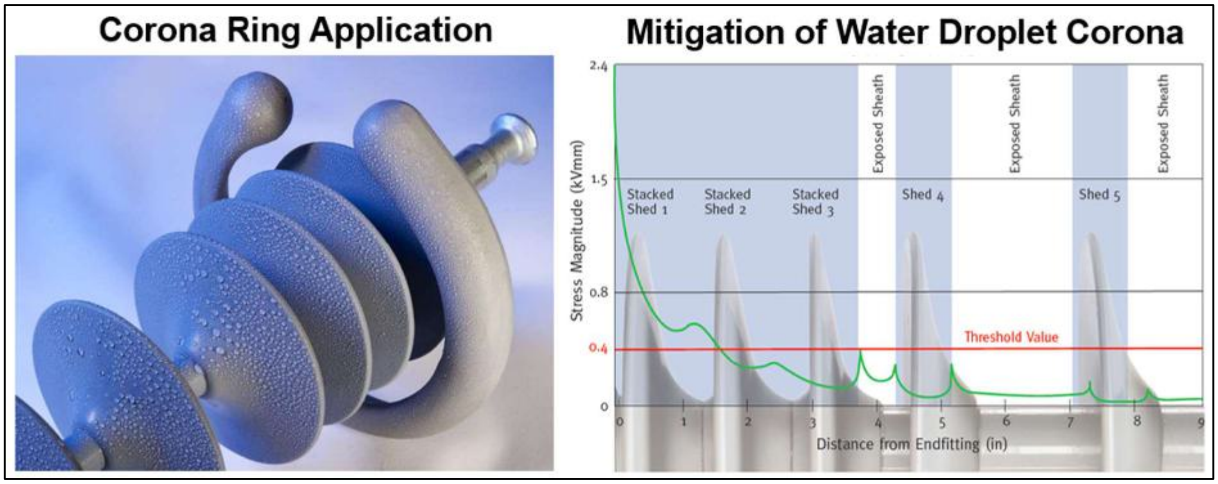
Sealing Systems:

- Evolved from basic or single-point seals to multi-layer, redundant sealing systems for enhanced moisture ingress protection.
- Polymer Specific Seal Tests
  - Corrosive Aging / Salt Fog Testing: Evaluates material durability under prolonged exposure to corrosive environments.
  - Acid & Caustic Exposure: Assesses seal resistance to acidic and alkaline substances.
  - Boiling Water Submersion
  - Dye Penetration Test: Detects defects in seal materials using fluorescent dyes.

Fig 6: Multi-Layer Seal Test

Corona Protection:

- Increased use of corona rings to manage electric field stress, visible and audible corona, especially in EHV applications.
- Application of the corona ring improved to ensure secure, consistent attachment of the corona ring to the end fitting, optimizing ring placement and location for effective electric field control and long-term protection.
- Corona rings are absolutely required for designs operating at 230 kV and above, including extra-high voltage (EHV) applications.
- Corona rings may also be required for certain 115 kV - 161 kV applications, particularly in configurations with reduced phase-to-phase spacing where electric field (E-field) stresses are magnified and focused.
- Mitigation of Water Droplet Corona – involves protecting the insulator sheath surface from localized corona discharge and E-field stresses at the line end of the insulator.

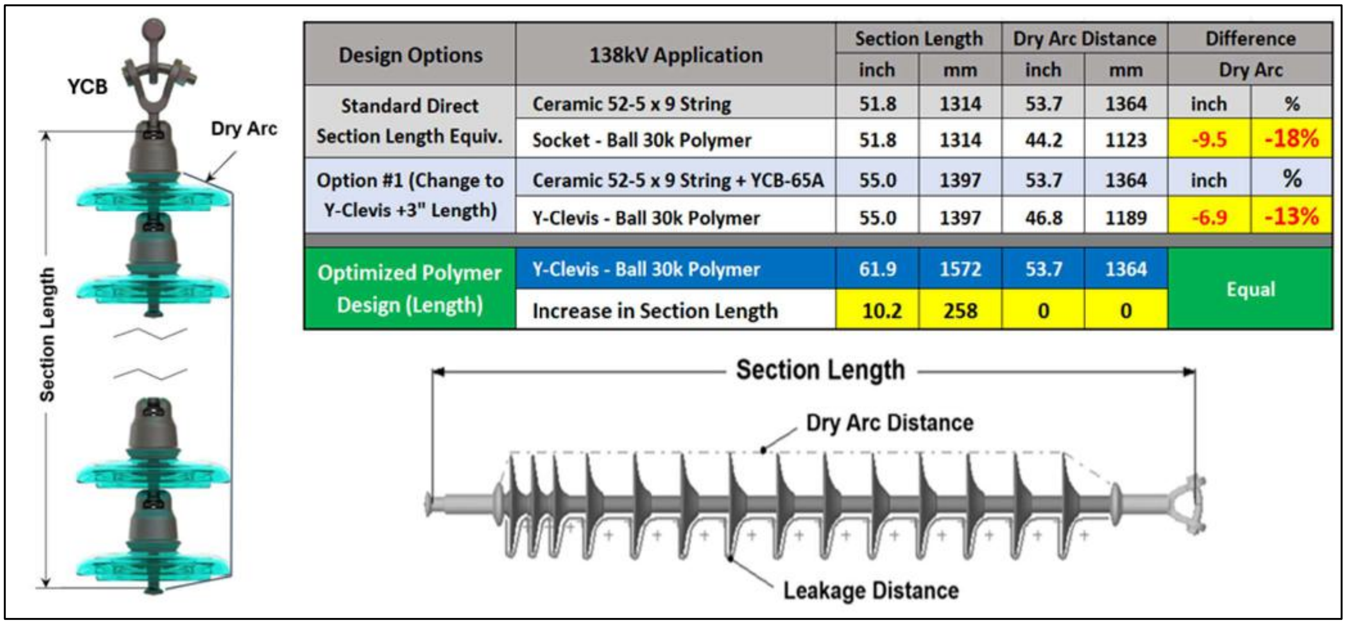

Corona Ring Application

Mitigation of Water Droplet Corona

Fig. 7: Corona Protection

Designed to Withstand the Environment: 2025 Design

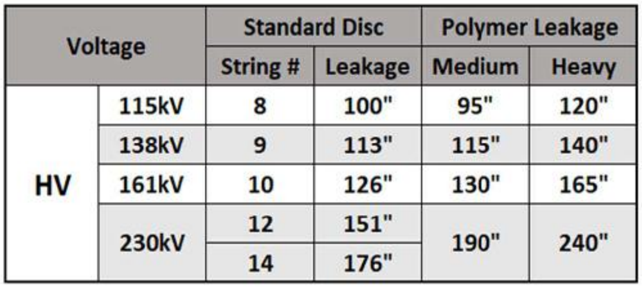
- Improved dry arc and leakage distances, enabling higher reliability, better contamination performance, and extended service life.
- Dry arc distance = the shortest metal-to-metal distance ≈ Air Gap
- Air gap is not specific to insulating media (ceramic or polymer)
- Polymer design criteria: Match ceramic dry arc / Not section length



Design Options	138kV Application	Section Length		Dry Arc Distance		Difference	
		inch	mm	inch	mm	Dry Arc	
Standard Direct Section Length Equiv.	Ceramic 52-5 x 9 String	51.8	1314	53.7	1364	inch	%
	Socket - Ball 30k Polymer	51.8	1314	44.2	1123	-9.5	-18%
Option #1 (Change to Y-Clevis +3" Length)	Ceramic 52-5 x 9 String + YCB-65A	55.0	1397	53.7	1364	inch	%
	Y-Clevis - Ball 30k Polymer	55.0	1397	46.8	1189	-6.9	-13%
Optimized Polymer Design (Length)	Y-Clevis - Ball 30k Polymer	61.9	1572	53.7	1364	Equal	
	Increase in Section Length	10.2	258	0	0		

Fig. 8: Disc Equivalent – Dry Arc Distance Polymer Design example

- Leakage (Creepage) Distance = the distance along the entire surface of the insulator housing; sheath & sheds.
- Contamination on the surface of the insulator enhances the chances of flashover.
- Contaminates = Dirt, Dust, Salt, Water, and Ambient Humidity.
- Design polymer with Heavy Leakage



Voltage		Standard Disc		Polymer Leakage	
		String #	Leakage	Medium	Heavy
HV	115kV	8	100"	95"	120"
	138kV	9	113"	115"	140"
	161kV	10	126"	130"	165"
	230kV	12	151"	190"	240"
		14	176"		

Fig. 9: HV Leakage Comparison Table

- Pollution Specific Shed Spacing & Profile
- Use S/P ratio to derive balance between the section length of the insulator and shed spacing in heavy leakage applications.
- Prevents tight shed spacing which could result in arc bridging across the length of the insulator, jumping shed tip to shed tip, in a wet condition.
- Target S/P ratio: HV Applications ≥ 1.0 [min ≥ 0.8]
- Target S/P ratio: EHV application ≥1.2
- Encourages a longer section length, in turn increasing the dry arc distance.

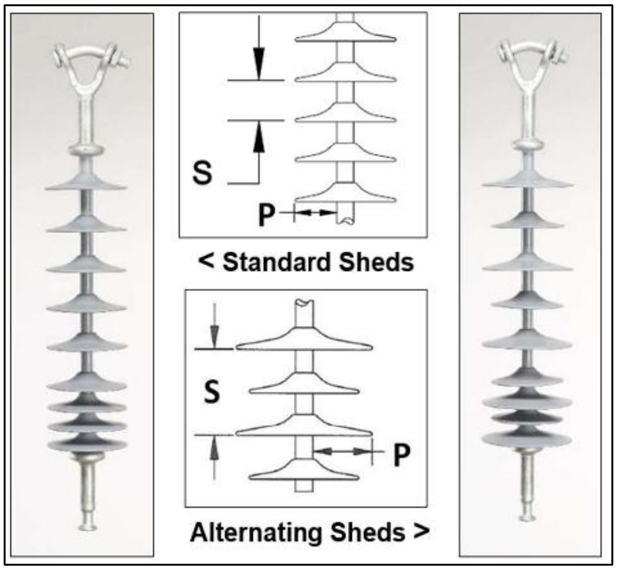


Fig. 10: Shed Spacing & Profile

Additional Considerations for Polymer Insulator Technology

- Supplier Track Record and Field Experience
  A proven history of successful installations and long-term field performance is essential when evaluating polymer insulator suppliers. This includes documented reliability across various voltage classes and environmental conditions.

- Ongoing Innovation and R&D Commitment
  Continuous improvement through research and development is critical. Modern polymer designs benefit from enhanced features such as improved hydrophobicity, optimized shed profiles, and advanced interface bonding techniques.

- Comprehensive Testing Protocols
  Suppliers must demonstrate a strong commitment to mechanical, electrical, material, and corona performance testing. This includes both routine production testing and type testing that exceeds minimum industry requirements.

- Stringent Manufacturing Quality Standards
  High-quality manufacturing processes (not specified or defined by industry standards) are vital for ensuring consistency and long-term reliability. This includes rigorous process control, traceability, and in-house testing capabilities.

Polymer insulator technology has significantly evolved since the introduction of first-generation designs in the 1980s. Improvements in materials, manufacturing processes, and quality control have led to more reliable and robust polymer insulators. Additionally, modern designs incorporate features that address many of the challenges observed in early-generation applications. Despite these advancements, some reservations remain regarding the use of polymer technology in extra-high voltage (EHV) applications. This section will address those concerns and outline the critical design, manufacturing, and application considerations necessary to ensure successful implementation of polymer insulators at 500kV and above.

Polymer Design Requirements for 500kV Applications – Keys to Longevity

Key #1 - Polymer Insulator Materials

- ✓ High Consistency Silicone Rubber Formulation
- ✓ Long-Term Service History
- ✓ HTV Silicone (High Temperature Vulcanize)
- ✓ Corrosion Resistant E-Glass (Boron Free)
- ✓ Corona Lip End Fittings
- ✓ EHV Appropriate Corona Rings

Key #2 - Polymer Insulator Manufacturing

- ✓ HTV Silicone Production Process
- ✓ Fully Bonded Housing to Core Interface
- ✓ Seamless, Continuous, Concentric Housing
- ✓ Controlled Compression Crimping of End Fittings
- ✓ Multi-Layer Sealing System

Key #3 - EHV Polymer Design

- ✓ Dry Arc Distance – Equivalent to Ceramic String
- ✓ Leakage Distance – appropriate for application environment
- ✓ Pollution Specific Shed Profile & S/P compliance
- ✓ Optimized E-Field Protection – Mitigate Corona Effects

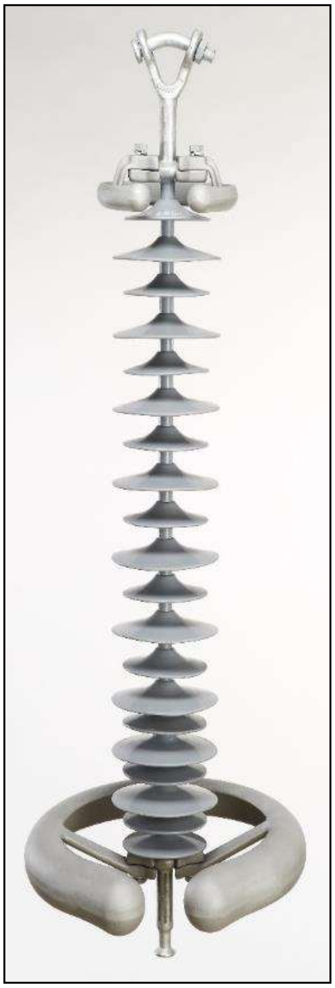


Fig. 11: 500kV Polymer

EHV Polymer Insulator Materials

Most of the requirements for polymer materials have been defined earlier in this paper. However, for extra-high voltage (EHV) applications, these requirements become even more critical. The silicone formulation used must be a well-established and stable compound, with consistent performance and a proven track record of more than 10 years in the field. Newly developed or modified formulations introduce risks due to potential imbalances in component composition and, more importantly, a lack of long-term field experience, an essential factor that cannot be fully replicated through laboratory testing alone.

500kV Polymer Materials: Key #1 to Longevity

✓ **Proven Silicone Formulation / HTV**:

Each manufacturer uses its own proprietary silicone formulation, and currently, there is no industry standard or guideline defining the ideal formulation for long-term performance.

For EHV applications, the approved polymer supplier should have a minimum of 10 years of field experience with their current silicone formulation. Additional credit should be given for each additional decade of proven service.

Fig. 12: Silicone Chemistry

✓ **Long-Term Service History**:

When it comes to EHV polymer performance, more experience is better - long-term reliability is directly tied to the maturity and stability of the formulation.

✓ **Corrosion Resistant E-Glass**:

Most manufacturers can provide CR-E upon request, while others offer it as a standard feature of their polymer designs. Ideally, an EHV supplier should include CR-E as a standard feature to eliminate concerns related to "brittle fracture"; and should have > 10 years' experience using CR-E (additional credit should be given for each additional decade of proven service.

Fig. 13: CR E-Glass Rod

Enhanced Performance of CR-E (Boron Free E-Glass)

- Superior Acid Resistance: Unlike traditional E-glass, where acids can lead to embrittlement and fracture, the composition of CR-E glass remains intact, offering significantly superior acid resistance. This makes it ideal for use in corrosive environments.
- Improved Electrical Properties: CR-E glass exhibits better electrical properties compared to traditional E-glass.
- Increased Tensile Strength in Pultrusion: Pultruded rods made with CR-E glass can have a 5-8% increase in tensile strength with a good crimp process.

✓ Corona Lip End Fittings

- Corona Grading: The larger outer diameter (OD) of the metal lip helps grade the electric field at the triple interface.
- This reduces corona discharge, which can lead to long-term degradation of the polymer housing and core rod.
- Arc Withstand Capability: The corona lip adds a greater mass of metal to withstand arc terminations during fault conditions, preventing exposure or damage to the fiberglass core rod.

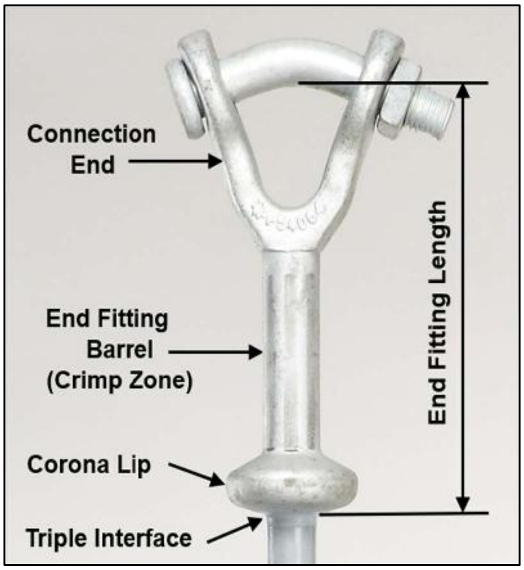


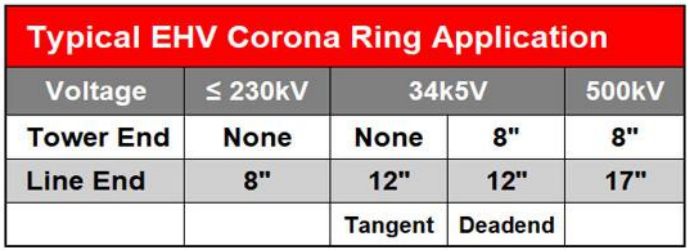
Fig. 14: End Fitting Geometry

- Corona Ring Mating Feature, the corona lip is a precision-engineered feature on the metal end fitting to facilitate the correct installation of a corona ring for optimal electrical performance.

✓ EHV Corona Ring

- Corona rings (grading rings) are metallic accessories installed on high-voltage insulators to control and distribute the electric field, reducing corona discharge, and minimizing RIV.
- Corona Rings are required on EHV Applications.

Fig. 15: EHV Corona Rings



Typical EHV Corona Ring Application				
Voltage	≤ 230kV	34k5V		500kV
Tower End	None	None	8"	8"
Line End	8"	12"	12"	17"
		Tangent	Deadend	

Fig. x: Corona Ring Application

- 500kV – 15-17" Line CR / 8" Tower CR
- 345kV – 11-12" Line CR / 8" Tower CR

*** Corona Rings are required at 500kV for all insulating media, including porcelain and toughened glass. Subject of a future INMR Paper!*

Fig. 16: Corona Ring Application

<u>500kV Polymer Manufacturing</u>: Key #2 to Longevity

In the manufacturing of high-temperature vulcanized (HTV) silicone insulators, selecting the right process is critical to ensuring performance and reliability across voltage classes. For high-voltage (HV) applications ranging from 69kV to 138kV, injection molding stands out as the ideal method due to its efficiency, consistency, and suitability for standardized designs. This process enables the complete encapsulation of the core rod in a single molding cycle—known as "single-shot" molding—making it perfect for insulators up to approximately 60 inches in length (single shot length is determined by the length of the molding press cavity). However, for longer insulators in the 161kV to 230kV range, injection molding requires a technique known as jump molding, where the housing is applied in two or more separate molding operations. While effective, this introduces potential seam lines that may impact long-term reliability, especially in more demanding environments & EHV Applications.

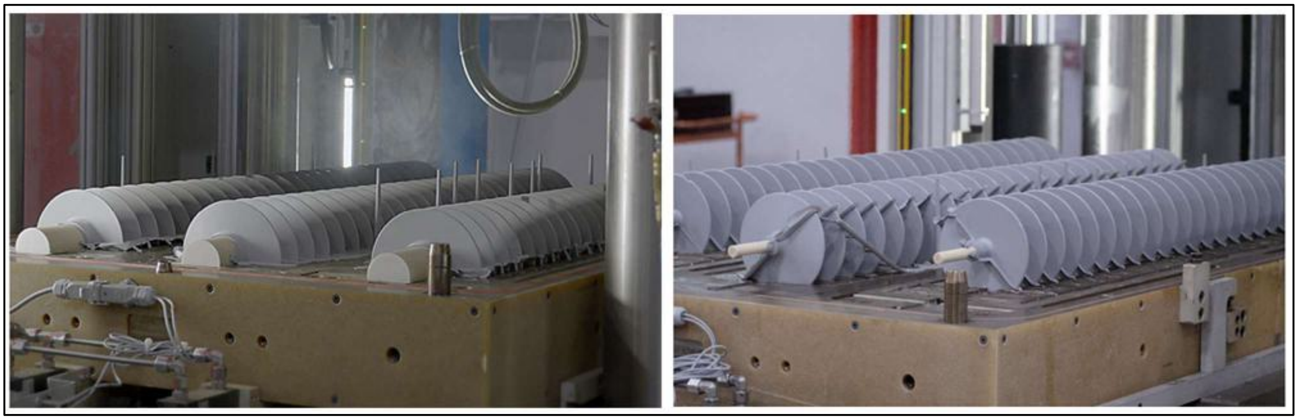


Fig. 17: Single Shot Molding of Line Post & Suspension Insulators

Quality concerns of manufacturing EHV insulator using Injection Jump Molding

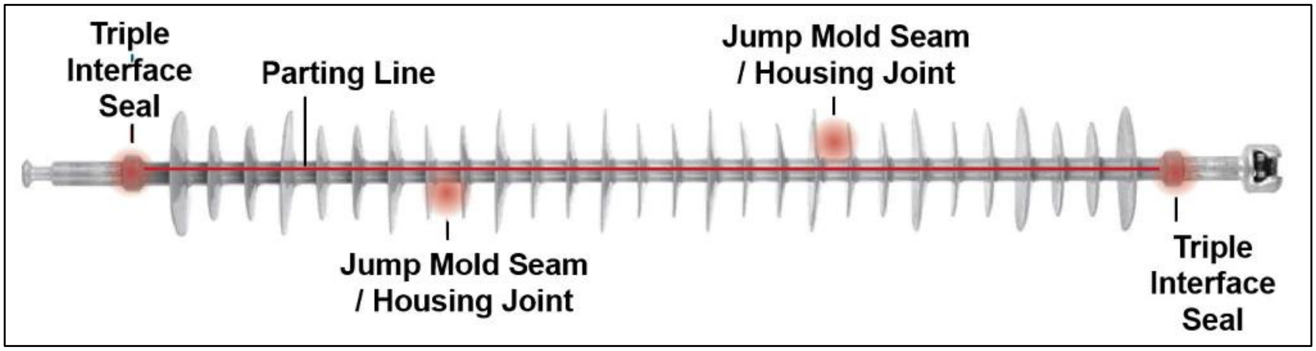


Fig. 18: Injection Molded Insulator

Fig. 19: Jump Molding

Parting Lines – One of the primary concerns when using injection molding for EHV insulators is the formation of parting lines—a continuous edge that runs along the entire length of the insulator housing, created by the two-piece mold cavity. Over time, these parting lines can become more pronounced due to tool wear in the mold cavities, compromising the uniformity of the silicone surface. These lines are susceptible to pollution and moisture accumulation, which can lead to leakage currents and significantly increase the risk of corona discharge.

Jump Molding – Injection molding relies heavily on maintaining consistent high temperatures to ensure proper bonding and curing of the silicone rubber to the core rod. In jump molding this consistency becomes difficult to maintain.

Each cycle introduces potential temperature fluctuations, which can compromise the integrity of the bond between silicone and rod. These variations may result in non-uniform curing, weak seam areas, and increased susceptibility to moisture ingress and electrical degradation—especially critical in EHV applications where long-term reliability is paramount.

Product Staging Between Mold Cycles: Risks in Jump Molding

Jump molding introduces operational complexity by requiring insulators to undergo multiple molding cycles. Between these mold cycles, partially molded sub-assemblies must be staged, often for extended periods. During this time, the materials naturally cool, necessitating additional preheating before the next molding cycle to ensure proper bonding. More critically, the exposed core rods are left vulnerable to dust, dirt, and other factory contaminants, which can compromise the integrity of the silicone bond. To maintain quality, these surfaces must be cleaned and re-primed, adding labor and variability to the process. The more jumps required, the greater the risk of contamination and inconsistency—factors that can directly impact the long-term performance of EHV insulators.

Molded Seams / Housing Joints – Any seams or joints in the silicone housing introduces a potential vulnerability which can compromise its effectiveness. Electricity behaves much like water: it seeks the path of least resistance and exploits it. Even a minor weakness in the housing can become a focal point for electrical activity on the sheath, leading to premature aging. Over time, these flaws can lead to performance degradation, short circuits, or even catastrophic failure (brittle fracture / flash-under).
To ensure long-term reliability, it's essential to minimize or eliminate seams and joints in silicone insulator wherever possible. A fully molded, seamless design provides the best defense against environmental and electrical stressors.

Core Rod Deflection – A manufacturing challenge in the injection molding of suspension insulators is maintaining rod-to-sheath concentricity. During the molding process, silicone is injected at high pressure, which can cause the rod to deflect downward toward the bottom of the mold cavity. This deflection is especially problematic in manufacturing EHV insulators. As a result, the sheath thickness may fall below the desired minimum of 3 mm in certain areas. These thin spots become focal points for electrical activity, such as partial discharge and tracking, which can accelerate material degradation and compromise the insulator's long-term performance.

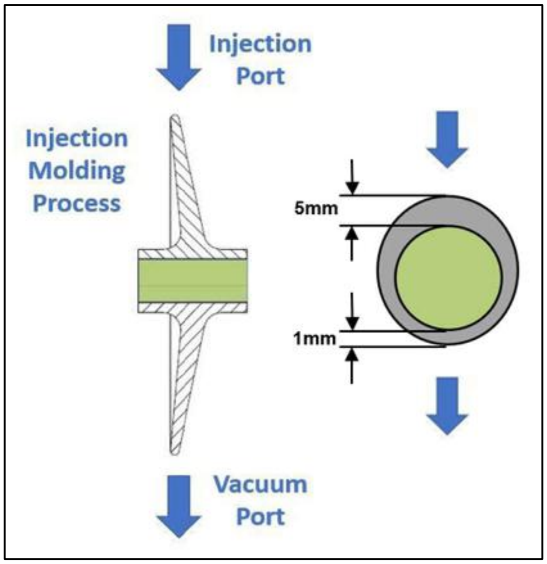


Fig. 20: Rod deflection

For extra-high voltage (EHV) polymer applications, minimizing potential sources of moisture ingress and electrical activity is essential to ensure long-term reliability and performance. Features such as parting lines, seams, and joints can act as entry points for moisture and focal areas for electrical stress, making their elimination or reduction critical. While injection molding, especially with advanced, state-of-the-art equipment, offers manufacturing efficiency and precision, it may not be the optimal design approach for EHV applications due to inherent risks like inconsistent sheath thickness and potential for defects. This does not mean polymer materials should be excluded from use at 500kV; rather, it highlights the need to carefully evaluate and overcome the risk/reward trade-offs associated with injection molding. Fortunately, solutions do exist to address these challenges and enable successful implementation of polymer insulators at high voltage levels.

Best Practice for Manufacturing 500kV Polymer Insulators

Extrusion Manufacturing Process – Seamless Insulation for Superior Performance

The silicone rubber is extruded, cured, and bonded directly onto the core rod in a continuous, uninterrupted process. This method applies uniform pressure from all sides, ensuring precise concentricity between the silicone sheath and the core rod. The extrusion is performed on rods ranging from 20 to 30 feet in length, maintaining consistent quality throughout.

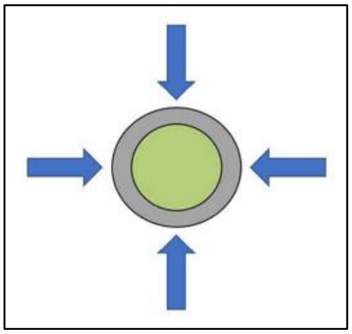


Fig. 21: Extrusion Process

Fig. 22: Extruded Sheath; Seamless, Continuous, Concentric Housing

A key advantage of this process is the creation of a seamless sheath. Unlike molded components that may have parting lines and joints, the extruded insulator features a continuous, uniform circumference with no axial seams. This eliminates potential weak points where electrical breakdowns could occur.

The result is a robust, high-integrity insulator with consistent bonding between the sheath and core along the entire length—critical for long-term electrical performance and reliability in demanding environments.

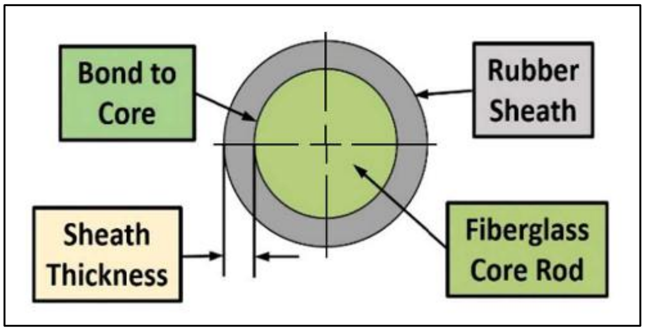


Fig. 22: Concentric sheath to rod

Manufacturing Features for 500kV Polymer:

- ✓ HTV Silicone Extrusion Application
- ✓ Fully Bonded Housing to Core
- ✓ Seamless, Continuous, Concentric Housing
- ✓ Controlled Compression Crimping of End Fittings
- ✓ Multi-Layer Sealing System

Next Step – Polymer Design for Success at 500kV

500kV Polymer Design – Key #3 to Longevity

Designing for success in EHV polymer applications means leveraging all lessons learned from earlier generations to strengthen areas that historically exhibited deficiencies. By building on past experience, we can enhance reliability, performance, and longevity, ensuring that 500kV polymer solutions are not only viable but optimized for demanding high-voltage environments.

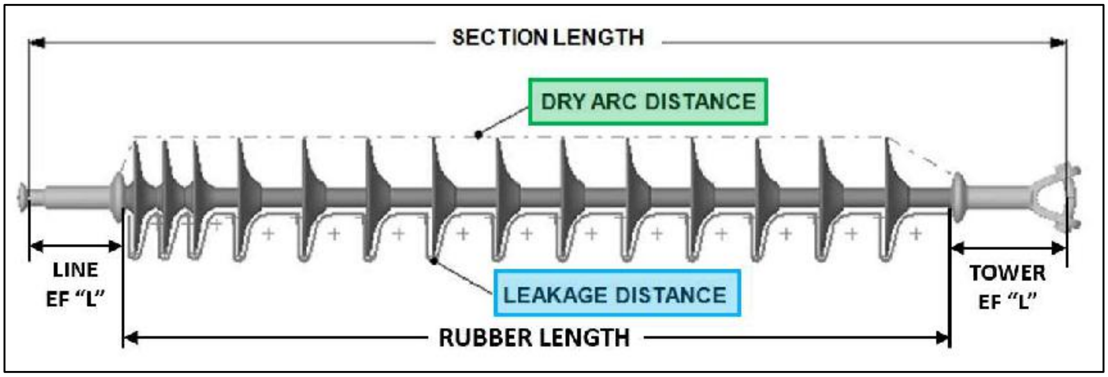
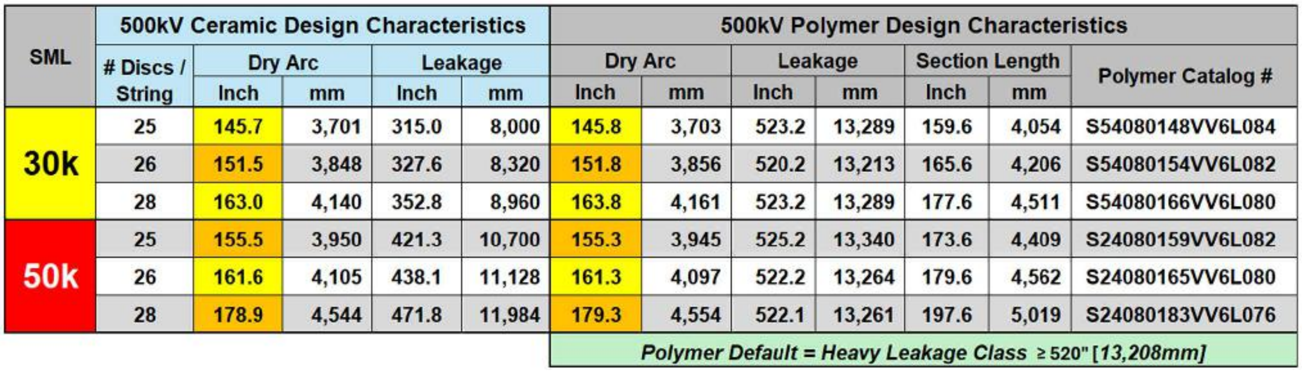


Fig. 23: Polymer Design Dimensions

- ✓ <u>Dry Arc Distance</u>

Dry arc distance refers to the shortest metal-to-metal distance through air, essentially representing the air gap between energized components. This measurement is independent of the insulating material used, meaning that when the air gap is equal, the electrical performance of different insulators—regardless of their composition—can be considered equivalent in terms of their electrical performance. In EHV applications, maintaining adequate dry arc distance is crucial for ensuring reliable insulation and minimizing the risk of flashover.



SML	500kV Ceramic Design Characteristics					500kV Polymer Design Characteristics						
	# Discs / String	Dry Arc		Leakage		Dry Arc		Leakage		Section Length		Polymer Catalog #
		Inch	mm	Inch	mm	Inch	mm	Inch	mm	Inch	mm	
30k	25	145.7	3,701	315.0	8,000	145.8	3,703	523.2	13,289	159.6	4,054	S54080148VV6L084
	26	151.5	3,848	327.6	8,320	151.8	3,856	520.2	13,213	165.6	4,206	S54080154VV6L082
	28	163.0	4,140	352.8	8,960	163.8	4,161	523.2	13,289	177.6	4,511	S54080166VV6L080
50k	25	155.5	3,950	421.3	10,700	155.3	3,945	525.2	13,340	173.6	4,409	S24080159VV6L082
	26	161.6	4,105	438.1	11,128	161.3	4,097	522.2	13,264	179.6	4,562	S24080165VV6L080
	28	178.9	4,544	471.8	11,984	179.3	4,554	522.1	13,261	197.6	5,019	S24080183VV6L076
						Polymer Default = Heavy Leakage Class ≥ 520" [13,208mm]						

Fig. 24: 500kV Design Table

For a 500kV polymer insulator, the dry arc distance should match that of an equivalent string of ceramic insulators to ensure comparable electrical performance. However, achieving this equivalence in polymer designs often results in a longer section length due to the continuous nature of the polymer sheath & longer metal end fittings. Fortunately, this added length can be effectively offset by reducing the length of the hardware components within the assembly, allowing the overall insulator design to remain practical while meeting performance requirements.

The images below show typical 500kV V-String, comparing ceramic and polymer insulator applications. The ceramic application includes a standard 25-disc string for 500kV.

Dry Arc Equivalent Designs		Section Length		Dry Arc Distance	
		Inch	mm	Inch	mm
Ceramic	25 x 52-11 Disc String	153.5	3899	155.3	3945
Polymer	**S24080159VV6L082**	**173.6**	**4409**	**155.3**	**3945**
	Length Difference:	**20**	**511**		
Optimized Polymer	**S24080186VV6S087**	**200.6**	**5095**	**182.3**	**4630**
	Length Difference:	**47**	**1196**	**27**	**686**

Fig. 25: 500kV Dry Arc Comparison

<u>Ceramic V-String Hardware</u>

- Y-Clevis / Ball Hot Line = 11”
- Oval Eye / Oval Eye Link = 84”
- Total connection length = **95”**

<u>Polymer V-String Hardware</u>

- Oval Eye / Oval Eye Link = 75”
- Steel Length Reduction = **20”**

The dry arc equivalent polymer for 50k SML has a 20” longer section length vs the ceramic string length. In most applications, this additional insulator length can be made to work with the assembly by reducing the length of the connection hardware. At EHV, the phase clearances are longer, requiring longer connection hardware offsets to maintain those clearances. Substituting addition polymer length and reducing steel length is beneficial to assembly performance and may reduce assembly hardware cost.

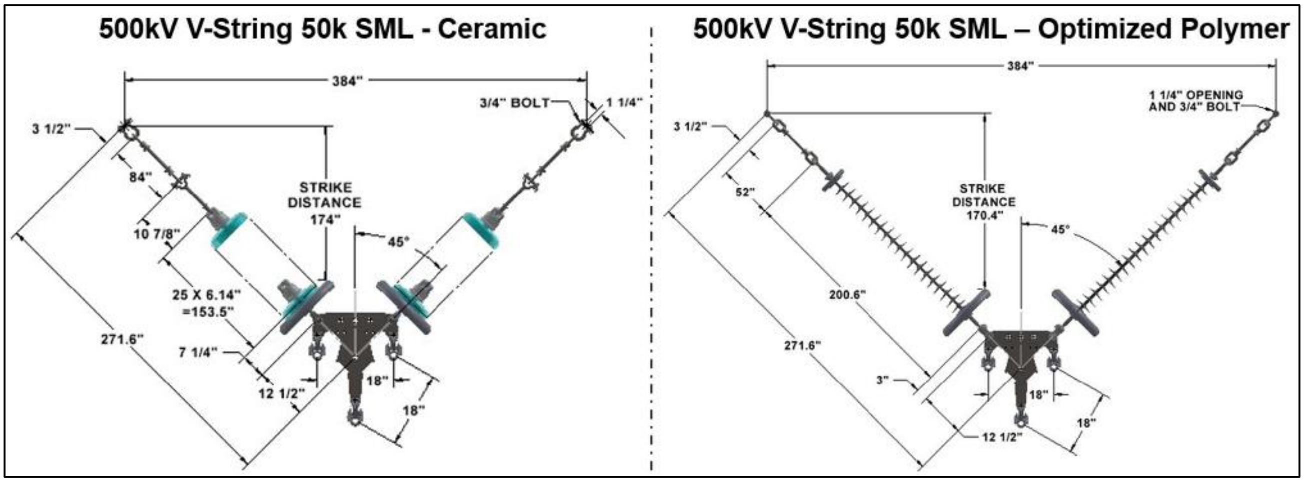


Fig. 26: 500kV V-String Comparison

In the <u>optimized polymer</u> 500kV V-string hardware design, the polymer section length has been extended by an additional 47 inches, directly increasing the dry arc distance 27 inches. This enhancement not only improves electrical performance, surpassing that of the original ceramic string, but also contributes to significant cost savings. In polymer design, increasing material length typically yields better performance, and the added cost of rod and rubber per inch is minimal compared to the much higher cost of steel hardware. By strategically reducing the length and complexity of the steel components in the assembly, the longer polymer section becomes a cost-effective and performance-enhancing solution.

✓ **Leakage (Creepage) Distance**

Leakage distance is defined as the metal-to-metal path traced along the entire surface profile of an insulator, and it plays a critical role in determining the insulator's ability to withstand environmental and contamination-related stresses. This distance must be sufficient to prevent flashover and surface tracking under polluted or wet conditions. Common contaminants include dirt, dust, salt, water, bird droppings, and ambient humidity. While often overlooked, humidity can be one of the most aggressive contaminants, as it facilitates the formation of conductive films on the insulator surface, especially when combined with other pollutants. In high-voltage applications, ensuring adequate leakage distance is essential for maintaining reliable performance and minimizing the risk of electrical discharge.

Matching the dry arc distance of a ceramic string is a baseline requirement when designing a polymer insulator for 500kV applications, as it ensures equivalent electrical performance under dry conditions. However, when it comes to leakage distance, it is not advisable to replicate the ceramic string design. The leakage distance of standard-profile ceramic string typically corresponds to performance suitable only for light to medium contamination environments, which is not ideal for long-term reliability in polymer applications.

Why should polymer leakage not match the equivalent leakage of the ceramic string?

A: When ceramic insulator strings begin to show signs of degradation, it is common practice to replace only the underperforming disc units—typically the bottom three discs of the string—through routine maintenance. Although this process addresses a performance issue, it is rarely classified as a failure. In contrast, polymer insulators do not allow partial replacement due to their monolithic design. As a result, any underperformance in a polymer unit necessitates full replacement, which is often labeled as failure. This creates a perception bias, where the same performance issue is judged more harshly in polymer applications than in ceramic ones, despite the functional equivalence of the degradation. Recognizing this discrepancy is important when evaluating long-term reliability and maintenance strategies for EHV insulation systems.

- The bare minimum leakage for 500kV polymer application is 20mm/kV (Medium Contamination), and this would be for non-coastal and less humid applications.
- The ideal recommended leakage for a 500kV Polymer would be to use 25mm/kV = Heavy Contamination (≥ 520" Leakage). See Appendix A for additional definitions of Environment Descriptions.
- For Coastal and other extreme contamination applications, default to 31mm/kV = Very Heavy Contamination (≥ 640" Leakage).

✓ Pollution Specific Shed Profile & S/P Compliance

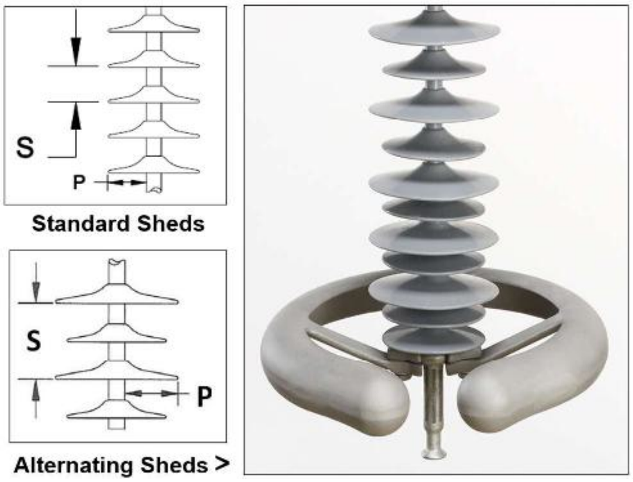


Fig. 27: Shed Profile & S/P

In addition to designing polymer insulators for heavy contamination environments, it is equally important to apply leakage distance using shed spacing that is appropriate for EHV applications. Shed spacing directly influences the effectiveness of the leakage path by controlling how contaminants and moisture are managed on the insulator surface.

Shed Profile Benefits

- Standard Sheds – best used on longer length (optimized) polymer.
- Alternating sheds are a strategic design feature best suited for standard-length polymer insulators with heavy leakage requirements, particularly in EHV applications. This approach helps prevent excessive shed compactness, which can lead to electrical activity bridging from shed tip to shed tip along the insulator's length. By alternating shed sizes—typically between large and small—designers can increase the distance between large, shed tips, reducing the likelihood of surface discharge and improving contamination performance. This spacing technique enhances the overall leakage path while maintaining electrical integrity, making it a preferred method for balancing performance and reliability in high-voltage environments.
- Desired S/P Ratio ≥ 1.2 [Optimized Design S/P = 1.5]

✓ Optimized E-Field Protection & Mitigation of Corona

EHV Corona Rings – 500kV

- ➢ Line End = 17" Corona Ring
- ➢ Tower End = 8" Corona Ring

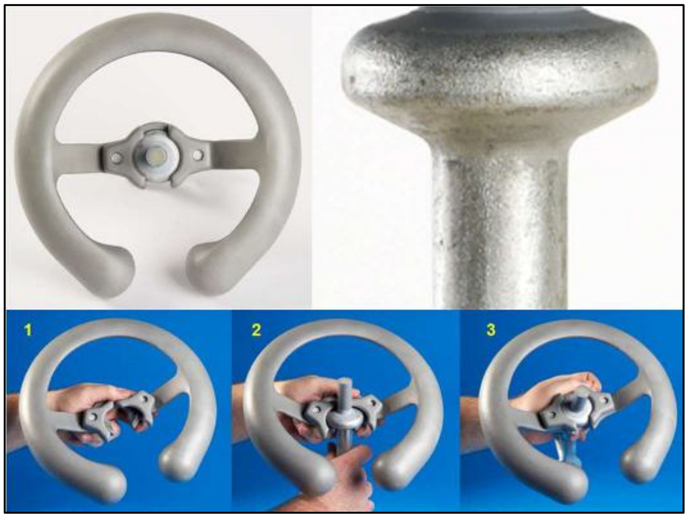


Fig. 28: Smart Fit Corona Ring

Corona Ring Attachment – "Smart Fit" corona ring refers to a design approach where the corona ring is mounted at a precisely defined location on the line end fittings of a polymer insulator. This ensures optimal corona protection by positioning the ring where it can most effectively manage electric field gradients and suppress corona. The Smart Fit concept includes a standardized mounting geometry, allowing contractors to install the ring quickly and accurately with minimal effort or guesswork. This not only improves installation efficiency but also enhances long-term performance and reliability in EHV applications.

Sheath Protection at 500kV Application

The sheath at the line-end of a polymer insulator—specifically the section between the end fitting and the first shed—is one of the most vulnerable areas in terms of electrical stress. This region is highly susceptible to elevated electric fields, corona discharge, and water droplet corona, even when equipped with corona rings. These stresses can lead to several degradation mechanisms, including loss of hydrophobicity, embrittlement of the silicone rubber, surface cracking, and moisture penetration into the core rod. Over time, these issues compromise the insulator's performance and reliability, making this area a critical focus in EHV polymer design and testing.

In addition to proper corona ring application, one effective solution for mitigating the vulnerability of the line-end sheath in polymer insulators is to increase the mass of silicone rubber in that region. This added material protects the sheath from electric field and corona stress. This concept is similar in principle to the use of a zinc sleeve on the pin of a ceramic disc insulator, which serves to protect against corrosion and pin necking.

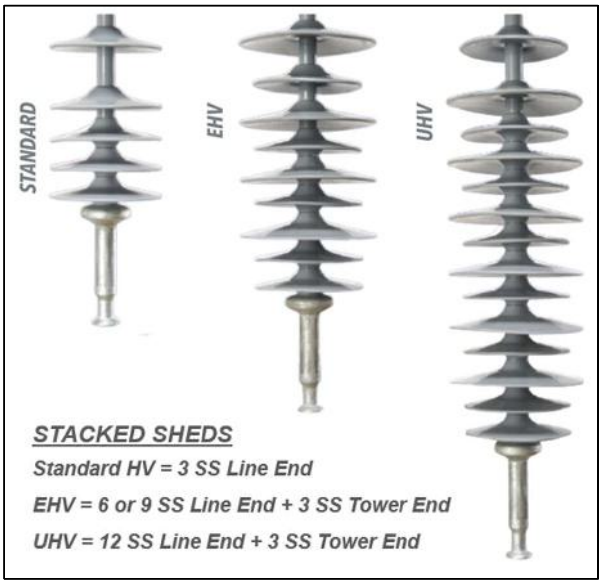
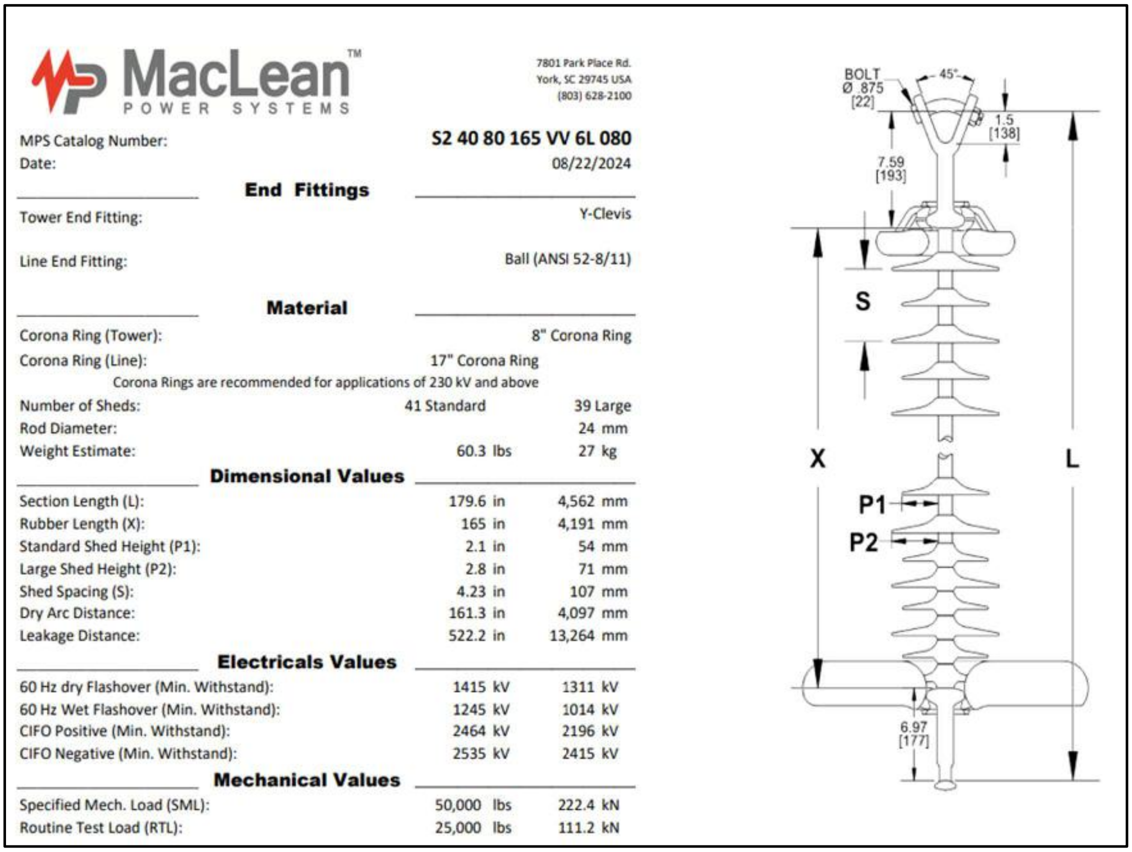


Fig. 29: Sheath Protection

One effective way to increase the silicone rubber mass at the line end of a polymer insulator is by incorporating stacked sheds into the design. These sheds maintain the same geometry as standard sheds but feature a large-radius underside. When stacked together, they eliminate exposed sheath between sheds and significantly increase the overall circumference of the silicone rubber in that region. This design not only protects the sheath from electrical stress but also prevents mechanical damage to the sheath in this critical area of the insulator.

Stacked sheds can be effectively applied to suspension insulators across all voltage levels, offering enhanced protection in areas of high electrical stress. Their placement is guided by E-field modeling, which identifies regions where the electrical stress exceeds 0.4 kV/mm. For HV applications, it is typical to add three stacked sheds at the line end of the insulator. In EHV applications, the number increases to six or nine stacked sheds at the line end, with an additional three stacked sheds at the tower end. This strategic addition of silicone mass strengthens the insulator's ability to withstand harsh environmental conditions and prolonged electrical stress, significantly improving long-term performance and reliability.

500kV Sample Polymer Insulator Design



MacLean™ POWER SYSTEMS

7801 Park Place Rd.
York, SC 29745 USA
(803) 628-2100

MPS Catalog Number:	**S2 40 80 165 VV 6L 080**
Date:	08/22/2024

End Fittings

Tower End Fitting:	Y-Clevis
Line End Fitting:	Ball (ANSI 52-8/11)

Material

Corona Ring (Tower):		8" Corona Ring
Corona Ring (Line):	17" Corona Ring	

Corona Rings are recommended for applications of 230 kV and above

Number of Sheds:	41 Standard	39 Large
Rod Diameter:		24 mm
Weight Estimate:	60.3 lbs	27 kg

Dimensional Values

Section Length (L):	179.6 in	4,562 mm
Rubber Length (X):	165 in	4,191 mm
Standard Shed Height (P1):	2.1 in	54 mm
Large Shed Height (P2):	2.8 in	71 mm
Shed Spacing (S):	4.23 in	107 mm
Dry Arc Distance:	161.3 in	4,097 mm
Leakage Distance:	522.2 in	13,264 mm

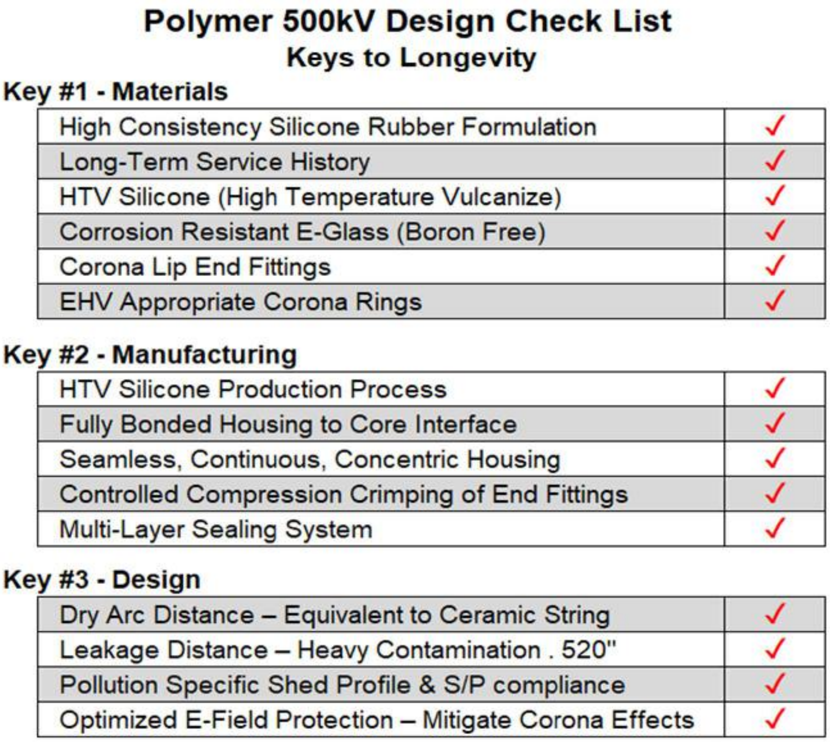
Electricals Values

60 Hz dry Flashover (Min. Withstand):	1415 kV	1311 kV
60 Hz Wet Flashover (Min. Withstand):	1245 kV	1014 kV
CIFO Positive (Min. Withstand):	2464 kV	2196 kV
CIFO Negative (Min. Withstand):	2535 kV	2415 kV

Mechanical Values

Specified Mech. Load (SML):	50,000 lbs	222.4 kN
Routine Test Load (RTL):	25,000 lbs	111.2 kN

Fig. 30: Proposed 500kV Polymer Design (minimum requirements)



Polymer 500kV Design Check List

Keys to Longevity

Key #1 - Materials

High Consistency Silicone Rubber Formulation	✓
Long-Term Service History	✓
HTV Silicone (High Temperature Vulcanize)	✓
Corrosion Resistant E-Glass (Boron Free)	✓
Corona Lip End Fittings	✓
EHV Appropriate Corona Rings	✓

Key #2 - Manufacturing

HTV Silicone Production Process	✓
Fully Bonded Housing to Core Interface	✓
Seamless, Continuous, Concentric Housing	✓
Controlled Compression Crimping of End Fittings	✓
Multi-Layer Sealing System	✓

Key #3 - Design

Dry Arc Distance – Equivalent to Ceramic String	✓
Leakage Distance – Heavy Contamination . 520"	✓
Pollution Specific Shed Profile & S/P compliance	✓
Optimized E-Field Protection – Mitigate Corona Effects	✓

Fig. 31: Design Check List

Conclusion

Polymer insulator technology has advanced significantly since the early generation designs that often failed to meet performance expectations. Today's polymer solutions benefit from major improvements in materials science, precision manufacturing, and application-specific design. These advancements have addressed historical weaknesses and enabled polymer insulators to meet the demanding requirements of EHV applications. However, not all polymer insulators are created equal. It is critical to scrutinize differences in materials, manufacturing processes, design expertise, and quality systems. Visiting the factory, observing how the insulators are made, and evaluating the quality assurance practices firsthand are essential steps in selecting a reliable product. In high-voltage environments, performance and longevity depend not just on technology, but on the integrity behind its production.

Next Steps

- Update specifications to address the keys to longevity covered in this paper.
- Proactively develop 500kV polymer designs and assemblies, have them ready to go should they be needed for projects or storm emergencies.
- Take advantage of the benefits of Polymer

Project Cost Saving

- Lower First Cost
- Lower Installation Cost
- Braced Post / Compact Line Design

Insulator Weight

- 1:10 Weight Ratio
- Polymer = Light Weight / High Strength

Transportation

- 1:5 Truck ratio
- Fewer Truck Loads of Polymer

Installation

- Less Handling
- Less Assembly

US Manufacturing!

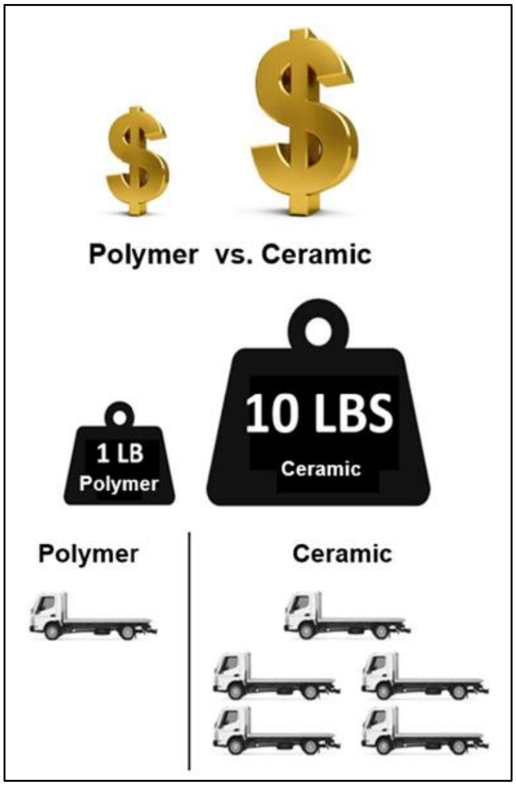
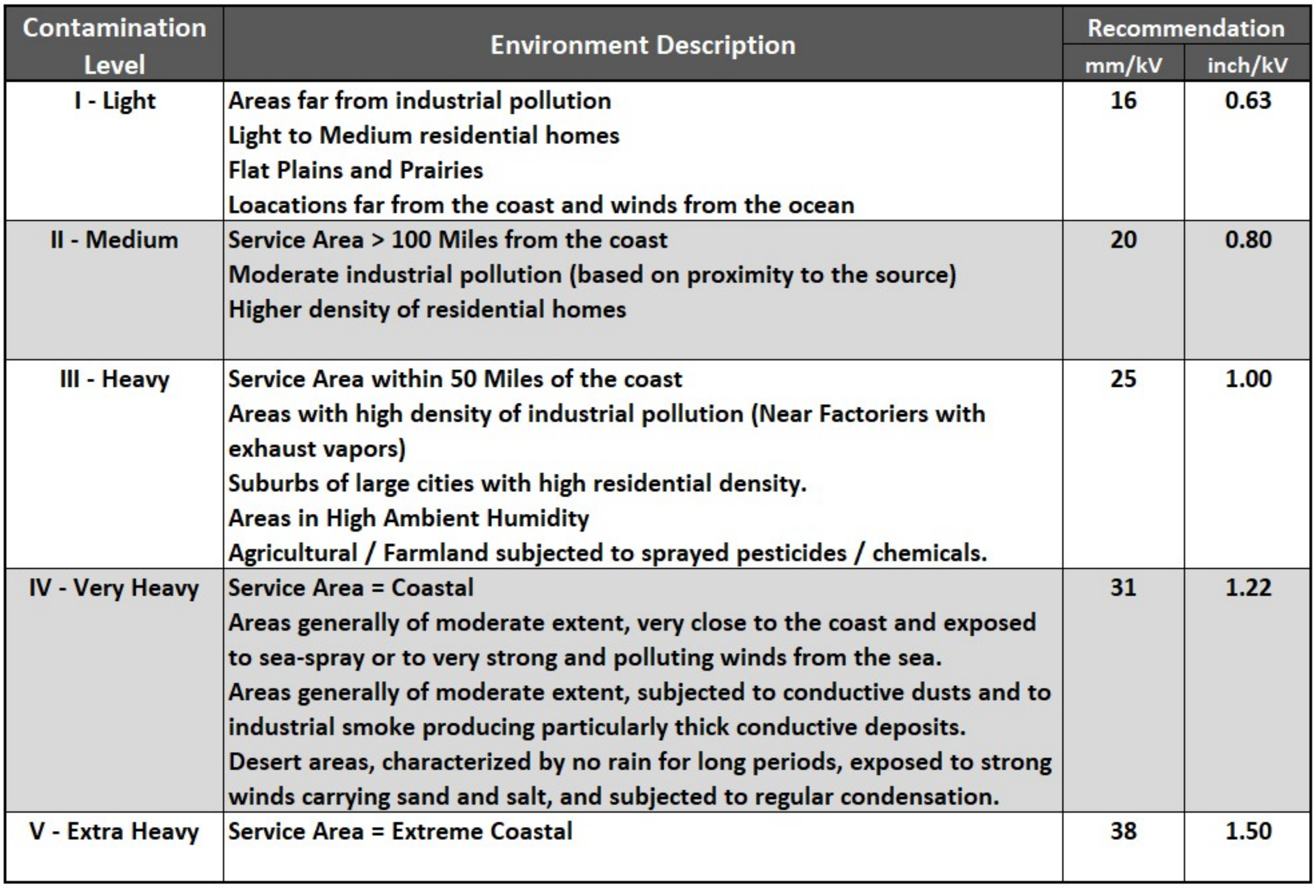


Fig. 32: Advantages of Polymer

Appendix A: Leakage Application Table



Contamination Level	Environment Description	Recommendation	
		mm/kV	inch/kV
I - Light	Areas far from industrial pollution Light to Medium residential homes Flat Plains and Prairies Loacations far from the coast and winds from the ocean	16	0.63
II - Medium	Service Area > 100 Miles from the coast Moderate industrial pollution (based on proximity to the source) Higher density of residential homes	20	0.80
III - Heavy	Service Area within 50 Miles of the coast Areas with high density of industrial pollution (Near Factoriers with exhaust vapors) Suburbs of large cities with high residential density. Areas in High Ambient Humidity Agricultural / Farmland subjected to sprayed pesticides / chemicals.	25	1.00
IV - Very Heavy	Service Area = Coastal Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting winds from the sea. Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits. Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation.	31	1.22
V - Extra Heavy	Service Area = Extreme Coastal	38	1.50

The table above was developed referencing information in Technical Standard IEC/TS 60185-3 [Selection and Dimensioning of high-voltage insulators intended for use in polluted conditions]