

INSULATED POWER CABLE



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Required performance

System options

- The **IEC standards** cover a range of cable types for a wide range of system performance requirements.
- **AC or DC?** Generally systems are AC, because of the benefits of **transformation** and of **3 phase**. However, high power links and long distance transmission feeders are often DC because of the need for synchronisation and because of cable capacitance.
- **Generation** is usually at **11 kV**, but generators exist up to 33 kV. These are characterised by high currents and very high fault levels.
- **Transmission** over distance is mostly done at extremely high voltages with overhead lines, AC or DC. If cables must be used the limits are about 500 km at 500 kV for DC and 100 km at 500 kV for AC. Single core cables.
- **Distribution** is up to **33 kV**. Extensive use is made of cables, mostly AC 3 phase, between stepdown substations and smaller distribution substations.
- **Reticulation** is the **LV** link to the final customer. Although load and fault handling is important, cables are frequently selected to suit volt drop limits.

Required performance

Voltage ranges

- Voltage ranges (AC) for cables and the IEC standards that cover them.

Rated Voltage	Type	Standard	Range of Application
1 050 & 1200 kV	UHV	None	Transmission of large blocks of power between countries and regions.
230 to 800 kV	EHV	IEC 62067 up to 500 kV	Transmission systems for bulk power and interconnector links between regions and cities.
35 to 230 kV	HV	IEC 60840	Transmission systems for feeding large block of power to city regions and towns.
1 to 35 kV	MV	IEC 60502-2	Distribution systems for feeding medium voltage systems and larger consumers such as shopping complexes, schools, hospitals, industrial plants, administration buildings etc.
< 1 kV	LV	IEC 60502-1	Reticulation and wiring systems for the feeding low voltage consumers such as houses, small workshops,

Required performance

- When specifying cables, many customers produce **construction standards**, as opposed to **performance standards**. The lower the voltage the more the standard is prescriptive about construction. Reputable cable manufacturers can handle both!

All or some of the requirements needed for **performance standards**:

- Proposed power transfer of the cable link
- Nature of current loading and contingency requirements
- System fault levels, symmetrical and earth-fault
- System power factor
- Harmonic content
- Details of the cable environment and weather conditions
- Accurate cable route measurements including changes of elevation
- Presence of other heat sources - including cables and other utilities
- Details of road crossings, ducts/pipes
- Details of any open air installation and exposure to direct sunlight
- Sending and receiving end cable arrangements into switchgear, outdoor

Required performance

When specifying cables, many customers produce **construction standards**, as opposed to **performance standards**. The lower the voltage the more the standard is prescriptive about construction. Reputable cable manufacturers can handle both!

Specifying cable **construction requirements**

- Length of cable required, and individual drum lengths
- **Voltage** designation
- Number of **cores**
- **Size** of phase conductor
- Conductor **material** (i.e. copper or aluminium)
- **Type** of conductor (i.e. stranded or solid)
- Type of **insulation** (i.e. XLPE or EPR)
- Type of metallic insulation **screen**
- Cross-sectional **area** of metallic insulation screen
- If an **armour** layer with a special construction is required
- Whether the cable is required to be **water-blocked**

Material selection

Metals (general)

The properties of all metals that have been used as conductors or barriers

Metal	Symbol	Density (kg/dm ³)	Conductivity		Resistivity (Ω.mm ² /km)
			IACS (%)	(S/m)	
Silver	Ag	10,5	105,5	61,23	16,3383
Copper (soft)	Cu	8,96	100	58,0	17,241
Gold	Au	19,3	72	41,76	23,946
Aluminium (H19)	Al	2,70	61	35,38	28,264
Calcium	Ca	1,54	46	26,68	37,481
Magnesium	Mg	1,74	43,8	25,40	39,364
Sodium	Na	0,97	37	21,45	46,62
Zinc	Zn	7,14	29	16,82	59,453
Nickel	Ni	8,90	24	13,92	71,839
Cadmium	Cd	8,69	23	13,34	74,962
Platinum	Pt	21,5	16	9,28	107,76
Tin	Sn	7,26	15	8,70	114,94
Lead	Pb	11,3	8,02	4,67	214

Material selection

Metals (general)

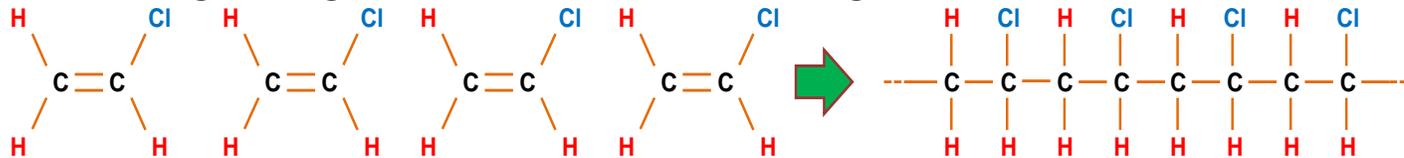
Comparison of copper and aluminium

Property	Unit	Al			Cu		
		Min	Standard	Max	Min	Standard	Max
Atomic number			13			29	
Electronegativity			1,61			1,90	
Standard reduction potential	E°(V)		-1,662			0,340	
Melting point	°C		659			1 065	
Density	g·cm ⁻³		2,70			8,89	
Specific gravity (to water)			2,70			8,89	
Resistivity at 20 °C	Ω·m	2,65E-08	2,83E-08		1,68E-08	1,72E-08	
Resistivity coeficient	K ⁻¹	4,03E-03	4,03E-03		3,93E-03	3,93E-03	
Resitivity at 70 °C	Ω·m	3,18E-08	3,40E-08		2,01E-08	2,06E-08	
Yield strength	MPa	15		20	117		314
Ultimate tensile strength	MPa	40		50	54		270
Expansion coefficient	K ⁻¹		2,30E-05			1,70E-05	
Specific heat	J/kg·K		955			423	

Material selection

Extruded polymers (PVC)

- **Polyvinyl Chloride (PVC)** is the second most produced plastic in the world, produced by **polymerising ethylene dichloride**, which is **hard opaque** white plastic.
- For use in cables we add **fillers, plasticizers, thermal stabilizers, and anti-oxidants**.
- Many others chemicals can be added giving **specific characteristics** such as colour, flame retardance, halogen reduction...etc
- Used for **insulation, bedding, filling interstices** and **sheathing**.



Extruded polymers (PE)

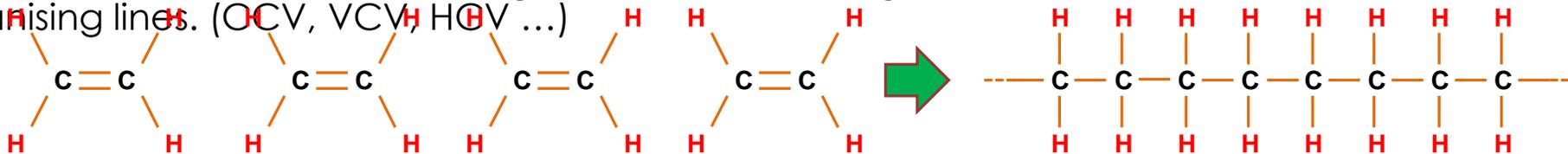
- **Polyethylene (PE)** is the most produced plastic in the world, produced by **polymerising ethylene** which is **partially opaque to transparent plastic**.
- The molecules can show variations, such as **side chain branching**. This can be used to categorise it by density. →
- A further density, linear low density (**LLDPE**) is produced by a more complicated process.
- The higher the density, the harder for the compound to be

ASTM 1248		
Type		Density (g/cm ³)
Very low	VLDPE	<0,910
Low (original)	LDPE	0,910-0,925
Medium	MDPE	0,926 – 0,940
High (linear)	HDPE	0,941-0,959
Very high	VHDPE	>0,959

Material selection

Extruded polymers (XLPE)

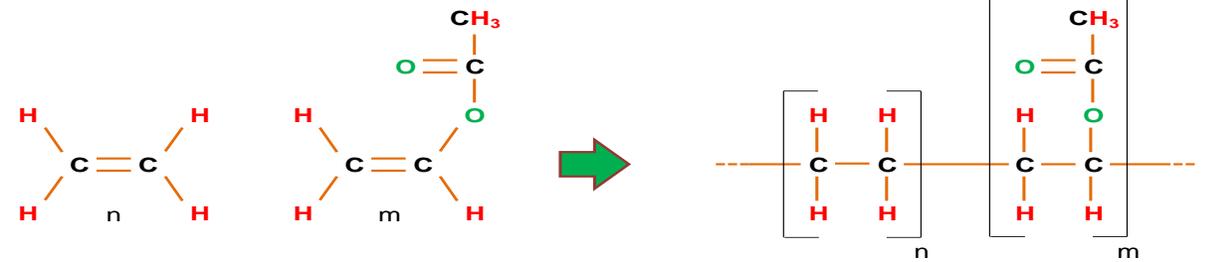
- **Crosslinked Polyethylene (XLPE)** is a PE that has been crosslinked, meaning that at some sites where the hydrogen atoms of adjacent chains align, they are removed and the chains are then bonded (crosslinked).
- The bonds can be **carbon to carbon**, but in some processes the **link can be more complicated**.
- In order for this to happen, the material supplier either includes **additives** with cross linkable XLPE, or these are added as the material is fed into the extruder. Depending on the process these can be **catalysts, peroxides, anti-oxidants, silanes**, etc.
- In the case of low voltages, other master batches can be added for **colour, UV stability** etc.
- At **higher voltages** this is a very highly **specialised** product, and the additives are engineered to not reduce the performance under electrical stress. **Hygiene is very crucial**.
- The material can be subject to **water trees** – a broad subject on its own.
- This used to be known as **vulcanising**, and manufacturing lines where this is done are to this day known as vulcanising lines. (OCV, VCV, HGV ...)



Material selection

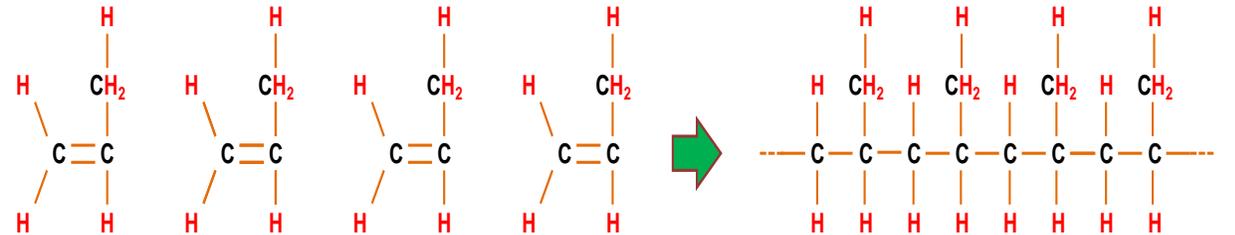
Extruded polymers (EVA)

- **Ethylene-vinyl Acetate (EVA)** is a more complicated polymer, produced by **polymerising ethylene and vinyl acetate together**
- It is both **low smoke emitting** and **halogen free**.
- It is used mostly as a **sheathing** compound, and can be highly filled for added properties.
- Not used for outdoor because of its weak mechanical protection.



Extruded polymers (PP)

- **Polypropylene (PP)** is produced by **polymerising propylene**.
- It is a very tough material and is mostly used as a **longitudinal fibrillated tape** as a interstice filler.

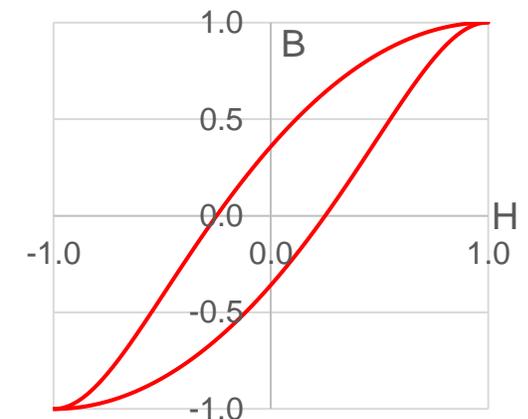
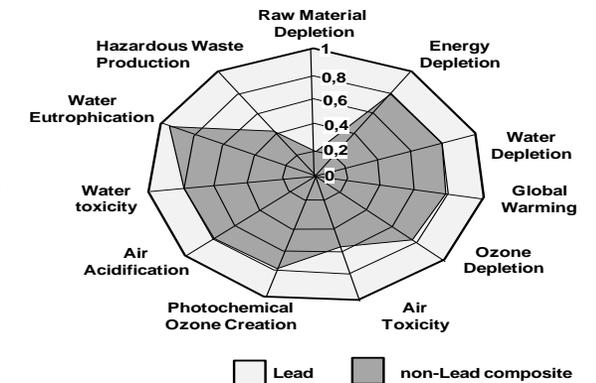


Environmental Aspects

Metals

- **Lead** is used for sheathing because it has the ability to **resist water** and **hydrocarbons**
 - It is a **neurotoxin**, and it can damage many organs and tissues, the environmental impact is shown .
 - It can enter the body by **inhalation** or **ingestion**, but not readily by absorption through the skin.
 - In PVC, **lead stabilizers** are being replaced with **calcium-zinc stabilizers**.
 - Pure lead will crack during transportation or after insulation but **lead alloy-E** is used to encounter the vibration
- **Steel** is used for cable armoring either as single (**SWA**) or double armor (**DWA**)
 - It is applied as a long lay length to provide **tensile strength** (370 MPa - 580 MPa)
 - Induced current will present and should be taken into consideration.
 - Steel armor produces a lag between **magnetic field** (H) and **magnetic flux density** (B) in alternating magnetic field where energy will transfer into heat (**hysteresis**)
 - Heat is also produced by the eddy current
 - **Steel tape** provides a good protection as a cover; however, it does not give tensile strength
 - Aluminum has a better use for **single core armoring**.

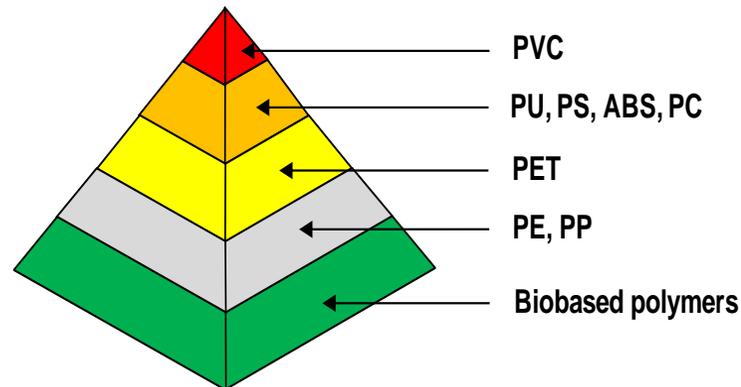
Ecoconception software EIME



Environmental Aspects

Recyclability

- Most of the cable materials can be covered and recycled
- **The exception:** Where metals have been **poisoned** to combat theft, such as the inclusion of a **brass wire in copper** or **copper coated aluminium**, then the same measures also prevent simple recycling.
- The common plastic components of cables, such as **PVC**, **PE** and **PP** can be recycled, although mostly not for their original purpose.
- **The exception:** Thermoset compounds that have been cross linked, such as **XLPE** and **XLEVA** cannot be re-melted, so have to be shredded and burned as fuel, or used as fillers.
- The **Greenpeace** plastic pyramid is shown on the right side

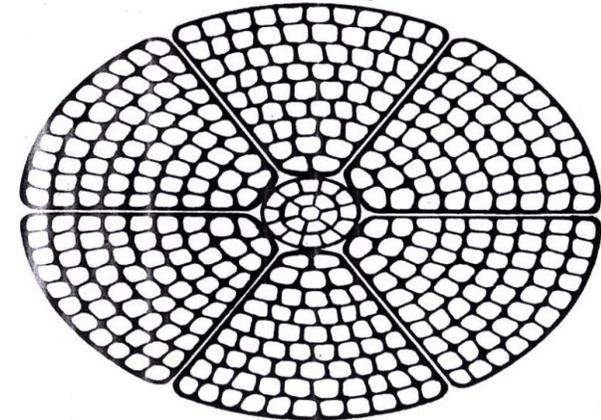


Cable design

Conductors – Conductor terms

- **Class 1** – (As per IEC 60228) Solid.
 - Conductors consist of single wires
 - **Class 2** – Stranded.
 - groups of wires neatly **stranded**
 - **Class 5** – Bunched flexible.
 - not-so-neat bunches wires **bunched**
 - **Class 6** – Bunched and more flexible than Class 5.
 - not-so-neat wires **bunched**, and they can be **round** or **sector**
-
- Note that the current density is higher at the surface of conductor at **high current** level, known as the **skin effect** which leads to higher **voltage drop**
 - To reduce this voltage drop, we split the conductor in segments (**Milliken conductor**) as shown

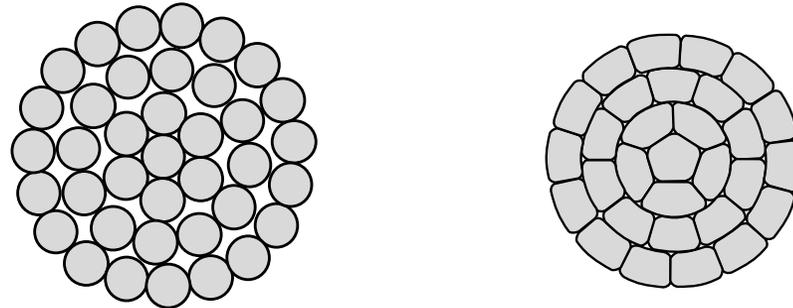
- The most common construction is **conventional lay stranding**:
 - The centre is a **single straight wire**, or occasionally a group of straight wires.
 - The concentric layers are **helical**, in **opposite directions**.
 - Stranded conductors are often **compacted** to reduce size while maintaining flexibility.
 - As compacting can increase **resistivity**, occasionally a wire will be omitted from a layer, improving resistance.



Cable design

Conductors – Conductor compaction

- Un-compacted conductors are **larger**, require **more material** on the layers above and result in **shorter lengths** on a drum. It is better to compact.



- Compacting **work-hardens** conductor. It also **increases its resistivity**, while it **reduces its area**, both **increasing resistance**.
- IEC 60228 defines conductor size by its **conductivity**, in other words by its resistance, so the manufacturer needs to **optimise** many parameters in deciding how much compaction to apply. Typical compaction will be 85% to 90%.
- After compaction the surface must be **free of edges** and irregularities.
- Conductor for **MV XLPE** must have a **compacted outer layer** to prevent penetration of semiconductor material.

Cable design

Screening

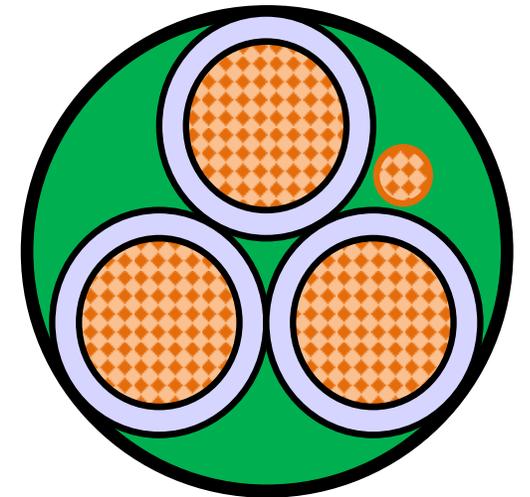
- No cable fault can occur on a screened cable without passing through the faulted core's screen. The screen therefore must be able to carry the **earth fault current**.
- Modern screens consist of a **semiconducting polymer** layer either bonded to, or very well attached to, the insulation. This ensures there are **no voids** between the insulation and the screen. Over the semiconducting layer will be a **metal** layer that will be able to carry **current**.
- **Copper wire** screens: The cross sectional area is the sum of the cross sectional areas of the wires. The spacing should be no more than 4 mm, however plasma formed during a fault has a very low resistance, so the wires will share current at a fault site.
- **Copper tape** screens: These are applied with a short lay and an overlay. However, even the smallest oxidation layer will prevent axial current. The cross sectional area is that of each tape only, and the path length is that of the helix.
- Screen constructions may also include **semiconducting water swellable tapes**, often spongy, where a cable is required to be water blocked.
- Copper tapes should not be used on large 33 kV single core cables. This is because during heat cycling the tape can be **strained** beyond the knee-point on its stress-strain characteristic.

Cable design

Filling

The interstices of the cables are packed with **fillers**, shown here in **green**.

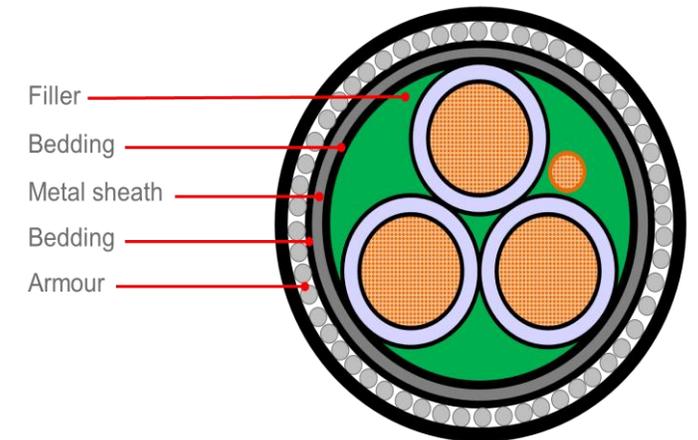
- This may seem to be the most trivial of the layers, but it is necessary where:
 - The cable needs to be **round** for handling, jointing and sealing purposes.
 - The cable is required to be **water blocked**.
- The **centre** interstice can be difficult to fill and water blocked, while still ensuring that the core metal screens remain in electrical contact.
- The **outer** interstices can be filled with:
 - **Pre-moulded** fillers.
 - **Extruded** fillers.
 - Polypropylene **fibrillated tape** fillers.
- Occasionally one or more **earth continuity conductors**, drain wires, or other insulated LV cores are included in the interstices. One is shown here.



Cable design

Bedding

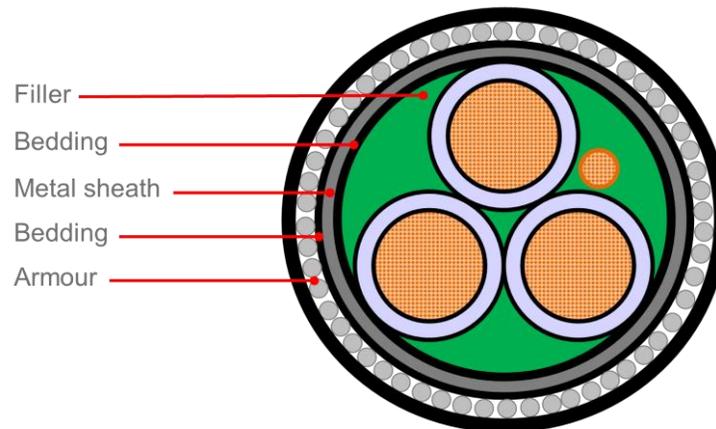
- The bedding is a **protective** layer that protects the more sensitive cores, with insulation and screens, from the harsher outer layers, such as the armour.
- It may also ensure that **dissimilar metals**, such as copper and steel, do not come into electrical contact.
- It may be of **lapped tape**, or **extruded**.
- Most standards specify very little about the properties of this layer – there are usually **no** mechanical or electrical requirements.
- During a fault it is **vaporised** rapidly by the plasma from the fault, bringing the screen and the armour into electrical contact.
- Cable has both a metal layer and an armour layer, then we usually apply a second bedding layer between the two.



Cable design

Metal sheath

- Other options than lead and steel:
 - **Smooth aluminium**, either **seamless or welded**, and **Aluminium tape**.
 - **Corrugated aluminium or copper**, either **seamless or welded**.
 - **Aluminium tape**, glued, bonded to the inside of a **polyethylene sheath**.
- **Lead** has **sufficient conductance** (8% IACS) for it to be treated as a conductor with respect to **induced voltages** and **currents**.
- However, it is mostly **incapable** of carrying **large earth faults** because of its low melting temperature, and relatively high resistance. Where this is required it may be augmented by **copper wires**.



Cable design

Jacket (Sheathing)

- Armour primarily **separates** the cable from its surroundings, during transport, installation and operation.
- The sheath is designed to **take punishment**, and **sustain** some damage, so that the layers of the cable beneath don't have to!
- **Sheathing compounds** as defined by IEC:

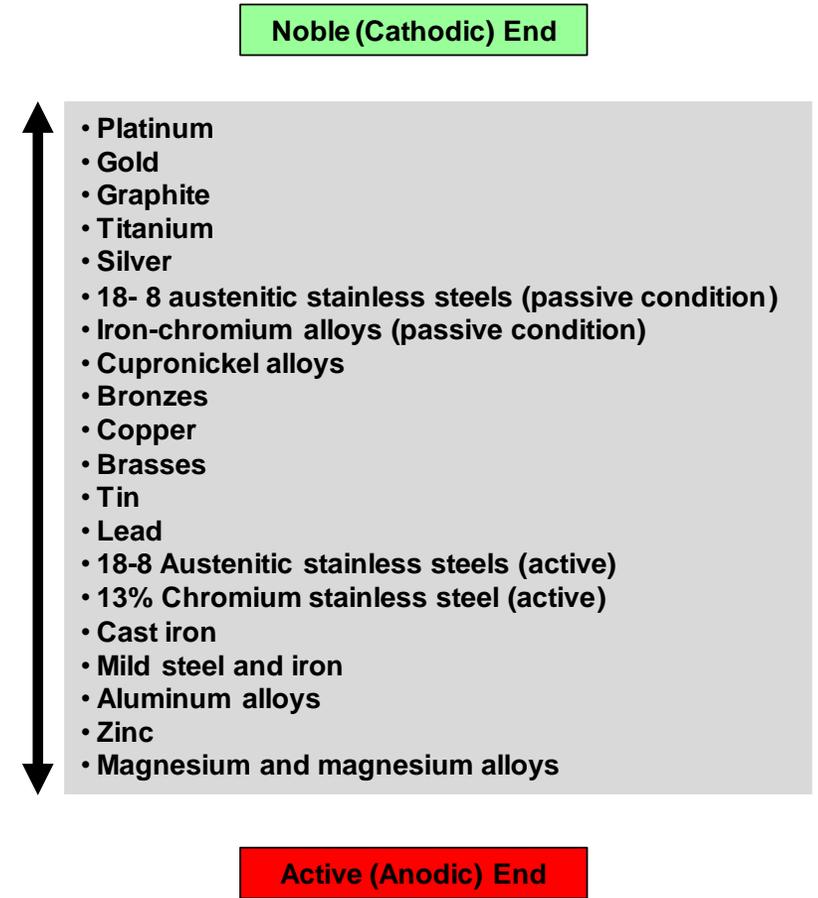
Sheathing compound	Abbreviated Designation	Max conductor temp in normal operation (°C)
Polyvinyl chloride (PVC)	ST1	80
	ST2	90
Polyethylene	ST3	80
	ST7	90
Halogen free	ST8	90
Polychloroprene, chlorosulfonated polyethylene or similar polymers	SE1	85

- PE sheathing offers **better mechanical** protection than PVC, and is also **reduces water ingress**.
- Where **sheath integrity testing** is required, the sheath radial is increased and a **semiconductive coating** is applied to the outer surface.

Cable design

Compatibility

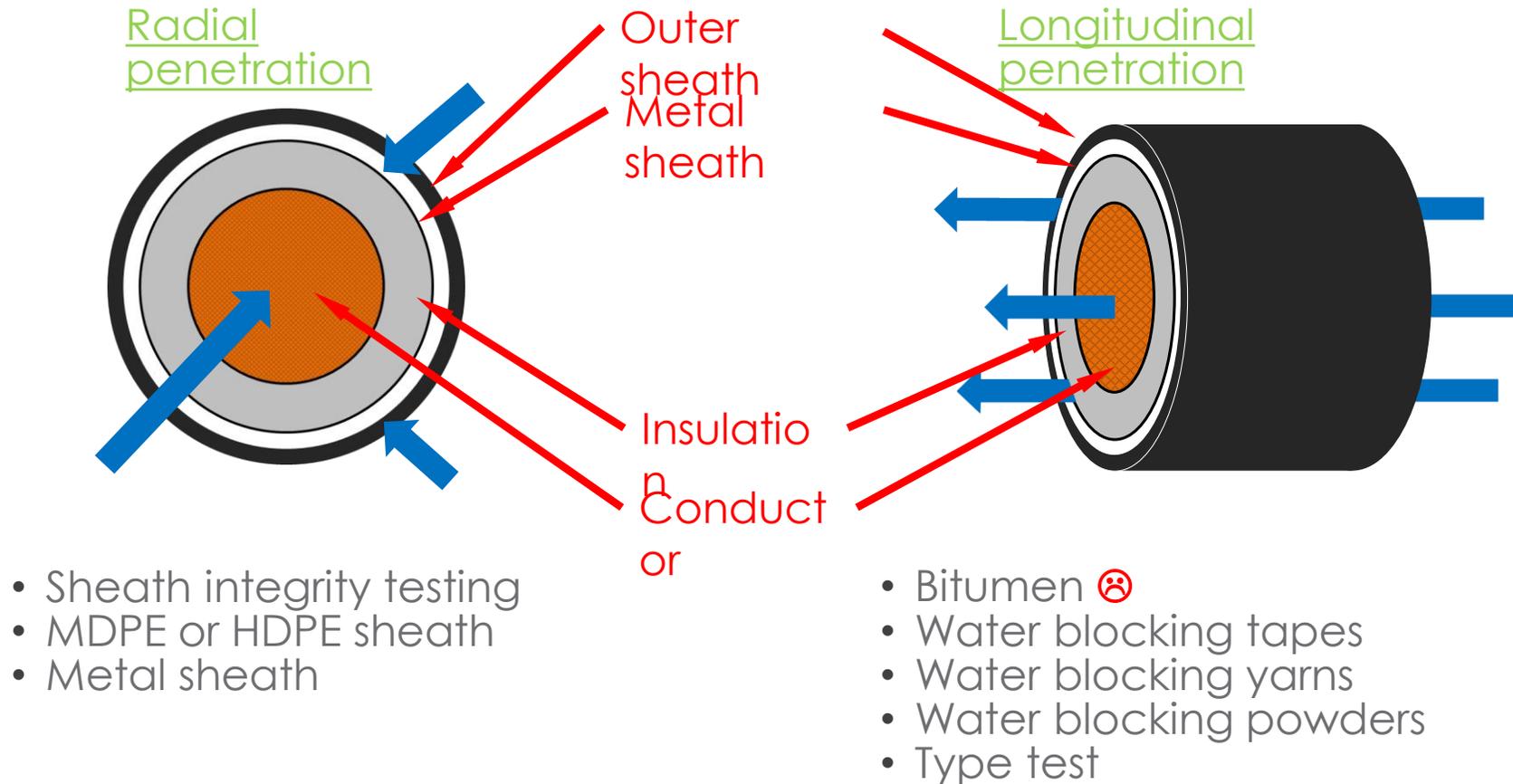
- This is the **ability** or otherwise of two materials to be **in contact** or close proximity to each other and still deliver the **expected performance** for the lifetime of the cable.
- **Metal-to-metal** galvanic corrosion occurs where metals having different **electrode potentials** are in **contact**, and placed in a medium that allows a current to flow.
- **Aluminium** is unusual because of the protection of its **oxide layer**. This fails when the pH is outside the range 4 to 9.
- **Polymer-to-metal**: Polyethylene undergoes a **catalytic deterioration** when in contact with **copper**. Therefore LV XLPE insulations must contain a copper deactivator. With MV XLPE they are not in contact.
- There is a **mechanical incompatibility** between XLPE and aluminium as the **friction** is very low. This can be an issue with ABC, and is fixed with suitable tapes.
- **Polymer-to-polymer**: PVC can contain **phthalate plasticisers** that can migrate into adjacent PE and XLPE, causing damage. Here separator tapes should be used, and the compatibility proven by testing.
- **Polymer-to-environment**: Detrimental interaction in a few ways.



Cable design

Compatibility

- **Cable-to-water:** Can promote water trees and corrode copper screens.



Thank You



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