Controlling Static on an Unwinding Roll

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ABSTRACT

High levels of static charge on insulating webs cause a number of problems in roll-to-roll manufacturing operations. Sparks shock operators, damage machine control systems, ignite flammable vapors, and change the surface chemistry of carefully formulated products. High levels of static charges attract contaminants and cause coating non-uniformities. Static charges on the web from previous operations or from tribocharging when a roll is unwound are difficult to neutralize.

Each time that a roll is unwound presents a unique opportunity to neutralize static. Described here is a method for neutralizing static on unwinding rolls that has three key elements. First, a high performance, long range static bar neutralizes the outside web surface on the unwinding roll. Second, a static bar must be located past the first conveyance roller to neutralize the inside surface of the web. And lastly, all conveyance rollers prior to the static bar that neutralizes the inside web surface must touch only the inside surface of the web.

This new neutralization method [1] is analyzed to show that static charge separated at the unwinding nip by tribocharging may be substantially reduced. And, the neutralization method reduces static charges from previous operations wound into the roll. The effect of the first conveyance roller on static control is critical. The web exiting the unwinding roll may have a high level of static that will cause pre-nip ionization in the gap between the web and the roller surface prior to contact. Pre-nip ionization requires that the first conveyance roller contact the inside surface of the web. When the first roller touches the outside surface, analysis shows that the charge neutralization performance is compromised. The web will remain highly charged through the production operation resulting in high static in the winding roll.

NOMENCLATURE

Table 1: Nomenclature

Parameter	Units	Description
A_{ROLL}	m^2	surface area of an unwinding roll (excludes side walls)
C_{ROLL}	F	capacitance of the unwinding roll
D_{CORE}	m	roll core diameter, inner diameter of unwinding roll
D_{ROLL}	m	outer diameter of unwinding roll
d_{WEB}	m	web thickness
E_{SPAN}	V/m	electric field measured on a web span
Q_{ROLL}	C	charge on the outside surface of an unwinding roll
V_{ROLL}	V	voltage (electric potential) of the unwinding roll
V_{WEB}	V	web surface potential
W_{WEB}	m	web width
ε_0	F/m	permittivity of free space; 8.854×10^{-12} F/m, physical constant
κ_{WEB}	1	dimensionless relative dielectric constant, material property
σ_{WEB}	C/m^2	web surface charge density
$\sigma_{WEB,IN}$	C/m^2	surface charge density on inside web surface
$\sigma_{WEB,OUT}$	C/m^2	surface charge density on outside web surface

1. INTRODUCTION

Improvements in printing, embossing and etching technologies enable roll-to-roll (RtR) manufacturing to be used to produce a wide variety of new products including flexible electronic circuits, electronic displays, solar cells, and biologically active sensors. These products each have carefully designed surfaces that provide high value to the end product. Static charges that accumulate during production processes on insulating polymer risk dust attraction and sparks that damage the carefully engineered surfaces, resetting machine control systems, igniting flammable solvent vapors, and injury operators.

Controlling static in RtR operations has been a challenge at least since the 1950's when electrostatic charge attracted dust to motion picture film [2]. New and emerging products produced using RtR operations will require better static control because electronic devices, thin layers of engineered materials, and biologically active layers are sensitive to contamination and changes in surface chemistry driven by static discharges.

Many devices for neutralizing static charge are available. These devices all ionize air using either a low energy corona discharge at the sharp tips of electrodes or ionizing radioactive elements. Static neutralizers can be broadly categorized at either passive or active. Passive devices include static brushes, tinsel, and ionizing strings that simply needed to be connected to ground potential to operate. For their operation, passive devices rely on the electric field from the static charge on the web. Passive neutralizers must be the nearest grounded object to the web, which usually requires that they be located very near the web surface, typically in the range 0 cm – 3 cm. When the electric field is low, passive device generate no ions. As a result, passive devices are ineffective in neutralizing static charge below a threshold surface charge density of about 2 $\mu C/m^2$.

Active neutralizers are energized either by a high voltage power supply or a radioactive element. These devices include nozzle ionizers, static blowers and static bars. Radioactive ionizers have a limited ionization output and they are commonly used in cleanroom applications where the residence time of charged objects in the ionization field is long. Corona ionizers are commonly used in RtR applications that require neutralizers having high ion output. The electrodes in corona neutralizers are typically energized by an alternating voltage waveform that generates corona ions of both polarities. Consequently, there is no turn-on threshold for operation and active ionizers can completely neutralize static charge. Ions generated by active ionizers are mobile and they can move a significant distance through the air from the energized electrodes to the web surface to be neutralized, typically in the range 1 cm – 10 cm.

Some modern static bars are designed to effectively neutralize charged objects at a long distance from the ionizer. The electrodes in these ionizers are energized by alternating voltage pulses rather than by a sinusoidal voltage. These long range ionizers can neutralize an unwinding roll at a distance in the range 0.5 m – 2 m.

These long range static bars enable this new method for neutralizing static charges on unwinding rolls. This new method is effective in neutralizing static charges on unwinding rolls from two common root causes; (1) tribocharging between the inner and outer surfaces of the unwinding web and (2) static charge wound into the roll from prior operations.

2. STATIC CHARGE ON UNWINDING ROLLS

2.1 Tribocharging between inside and outside web surfaces

When two chemically different surfaces touch and separate, charge separates by triboelectrification. One surface will have positive charge and the other will have an equal amount of negative charge. Triboelectrification is a common source of static when unwinding laminates or coated webs because the inside surface is chemically different from the outside surface. In Figure 1, the inside surface of the web separates from the outside surface at the unwinding nip. In this case, the inside surface has a positive charge and the outside surface has negative charge after separation.

While tribocharging is well documented, it is not well understood. The triboelectric series in Table 2 provides guidance on the polarity and magnitude of charges on surfaces that touch and separate. For example, human skin is a biological material at the top of the triboelectric series and PET is a synthetic polymer near the bottom. After a human touches a PET web, the skin will have a positive static charge because it is higher on the triboelectric series. A "finger print" of negative charge will be on the PET web surface because it has a lower position. Generally, greater separation on the triboelectric series indicates greater charging between surfaces. For example, a coating with a polyurethane binder is triboelectrically well suited for a cellophane web to minimize tribocharging because these two materials are adjacent on the triboelectric series.

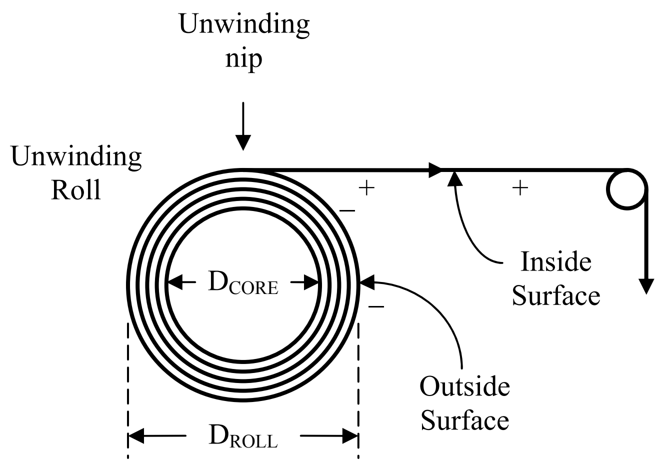


Figure 1: The web separates from the roll at the unwinding nip. In this example, the inside surface has positive charge and the outside surface has an equal amount of negative charge.

Many materials are missing from this version of the triboelectric series and most materials remain to be tested to determine their location. In this version, I have categorized materials to provide guidance on the position of unlisted materials. For example, polyvinyl chloride is the only entry for chloropolymers. Other chlorine containing hydrocarbons should have charging properties similar to PVC. Note that there are several exceptions. For example, nylon is a synthetic polymer that charges much more positively than would be expected. So, the charging properties of an unlisted material should be tested to confirm its location in the triboelectric series.

As the roll in Figure 2 continues to unwind, the exiting web is electrically neutral having a positive charge density on the inside surface and an equal negative charge density on the outside surface. When tribocharging is the source of static, the electric field E_{SPAN} measured on the first span is approximately zero, while the voltage on the unwinding roll is very high.

The voltage on the unwinding roll may be found by (1) if the capacitance C_{ROLL} is known.

$$Q_{ROLL} = C_{ROLL} V_{ROLL} \tag{1}$$

The charge Q_{ROLL} on the surface of the roll can be written in terms of the web charge density σ_{WEB} in (2).

$$Q_{ROLL} = \sigma_{WEB} A_{ROLL} = \sigma_{WEB}\left(\pi\, D_{ROLL}\, W_{WEB}\right) \tag{2}$$

The roll capacitance C_{ROLL} is estimated in (3) as the capacitance between concentric cylinders [4].

$$C_{ROLL} = \frac{2\,\pi\,\kappa_{WEB}\,\varepsilon_0\,W_{WEB}}{\ln\left(\dfrac{D_{ROLL}}{D_{CORE}}\right)} \tag{3}$$

Solve (1) for V_{ROLL} and use (2) and (3) to find (4) that is plotted in Figure 3 for a 0.1 m (~4 inch) roll core diameter.

$$V_{ROLL} = \frac{\sigma_{WEB} D_{ROLL}}{2\;\kappa_{WEB}\,\varepsilon_0} \ln\left(\frac{D_{ROLL}}{D_{CORE}}\right) \tag{4}$$

For a surface charge density of 1 $\mu C/m^2$, which is typical of tribocharging, the voltage of large rolls (1 m diameter) can exceed 50 KV. This voltage is sufficiently high to cause sparks from the roll surface to the core along the sidewall of the roll. Sparks may also occur between the roll surface and nearby grounded objects such as the machine frame or operators.

Table 2: Triboelectric Series [3]

Less human processing	Positive	inorganics & biological materials	human skin
			asbestos
			glass
			human hair
			mica
		exception	nylon
		inorganics & biological materials	wool
			cat fur
			silk
			alumina
		natural fibers	paper
			cotton
			wood
	Nearly Neutral	exceptions	steel
			poly(methyl methacrylate) (Elvacite®)
		natural resins	wax
			amber
			latex
		metals	copper
			brass
			gold
			platinum
	Negative	exceptions	synthetic rubber (neoprene)
			sulfur
		biopolymers	acetate (Rayon®)
			acrylic (Orlon®)
			cellophane
		synthetic polymers	polyurethane
			polycarbonate
			polyvinylidene chloride (Saran®)
			polystyrene
			polyethylene
			polypropylene
			polyimide
			polyethylene terephthalate (PET)
		chloropolymers	polyvinyl chloride (PVC)
		fluoropolymers	polychloro trifluoro ethylene (PCTFE)
			polyvinylidene fluoride (Kynar®)
			polytetrafluoroethylene (PTFE) (Teflon®)
More human processing		exception	silicone rubber

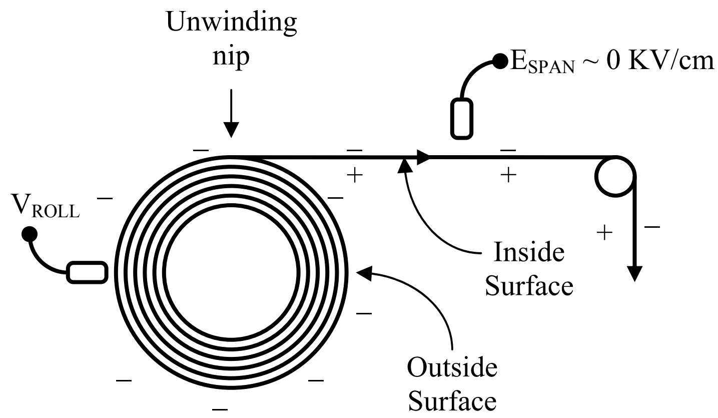


Figure 2: When tribocharging is the source of static, the electric field measured on the first web span is approximately zero. However, the voltage on the unwinding roll is very high and can exceed 50 KV. The voltage can cause sparks from the roll surface to the core or to other nearby grounded objects.

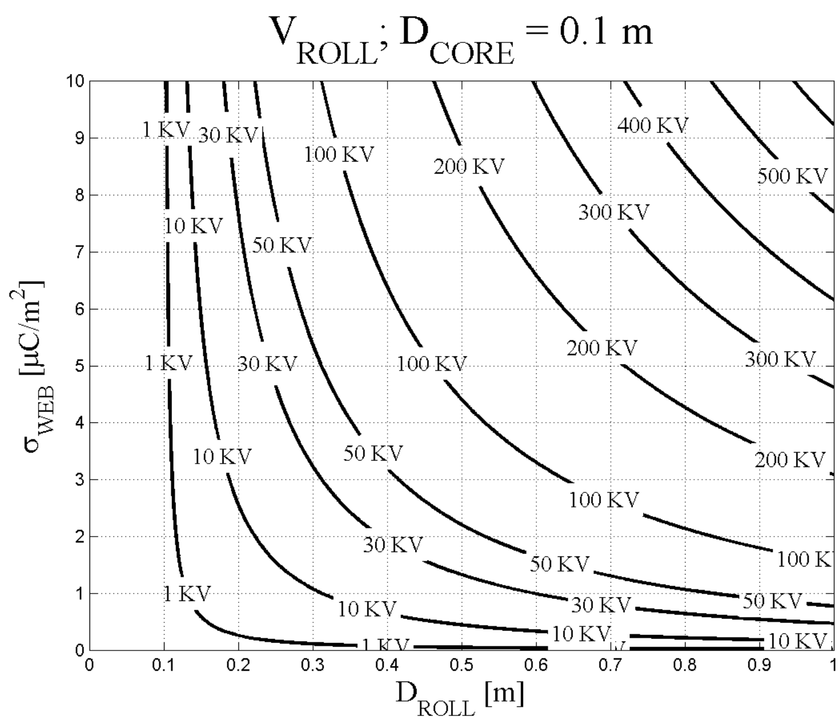


Figure 3: For a web charge density σ_{WEB} of 1 $\mu C/m^2$ that is typical of tribocharging, the voltage of a large unwinding roll (D_{ROLL} ~ 1 m) can exceed 50 KV.

2.2 Static charge from previous operations

A very common root cause for static problems is shown in Figure 4 where a web with positive charge on one surface and an equal amount of negative charge on the other surface is wound onto a roll. As the roll continues to wind, the positive charge on the outside lap of the roll is balanced by the negative charge on the web that forms the next lap.

The winding roll in Figure 5 has positive charge only on the outer lap that is electrically analogous to the unwinding roll in Figure 2. The analysis (1) through (4) and Figure 3 apply to this winding roll.

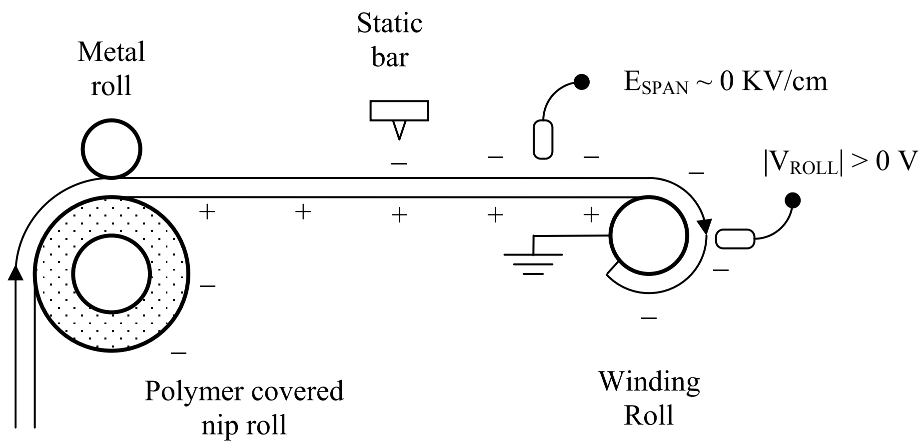


Figure 4: The web is charged by contact with the polymer covered nip roller. The static bar is located on the wrong side of the web, which results in negative charges on the outside surface and an equal number of positive charges on the inside surface of the web.

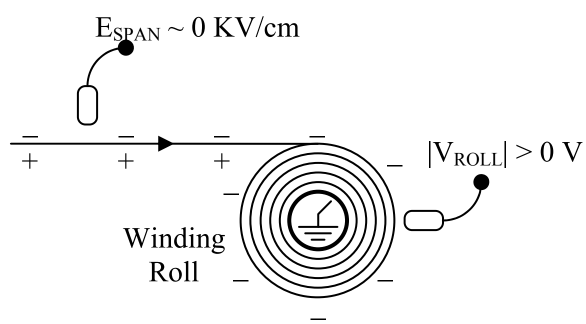


Figure 5: The web with positive charge on the inside surface and an equal amount of negative charge on the outside surface is wound resulting in negative charge on the outside surface of the roll.

The web surface charge density in Figure 6 may be measured using a non-contacting electrostatic voltmeter. The web thickness d_{WEB} is much smaller than the radius of the grounded metal roller, so the measurement geometry is approximately planar. The surface potential V_{WEB} is related to the surface charge density $\sigma_{WEB,OUT}$ by the capacitance of a parallel plate geometry as in (5).

$$\sigma_{WEB,OUT} = \frac{\kappa_{WEB}\ \varepsilon_0}{d_{WEB}} V_{WEB} \tag{5}$$

For a 50 μm thick (2 mil) PET web (relative dielectric constant $\kappa_{WEB} = 3.0$), a typical surface potential of 10 volts represents a surface charge density $\sigma_{WEB,OUT}$ of 5 $\mu C/m^2$. Even though the electric field E_{SPAN} on the span leading to the winding roll is zero, Figure 3 shows that the surface potential of this winding roll can easily exceed 100KV.

When this roll is unwound in the next operation, the charge distribution is identical to that in Figure 2. The static observed when unwinding a web with this very common pattern of charge, where one side has positive charge and the other side has an equal amount of negative charge, is indistinguishable from tribocharging. This is significant for two reasons. First, a method that effectively neutralizes unwind tribocharging will also neutralize this pattern of static charge on the web from previous operations. Second, during the development and commercialization of new products, coatings and laminates are formulated to minimize unwind tribocharging.

However, this tribocharging must be evaluated using rolls wound with an electrically neutral web because static charge from conveyance will be indistinguishable from unwind tribocharging. These two root causes of static are quite different and require uniquely different solutions. The solution for conveyance charging is the proper selection and location of static neutralizers along the conveyance path. In contrast, unwind tribocharging must be solved by adjusting the product formulation.

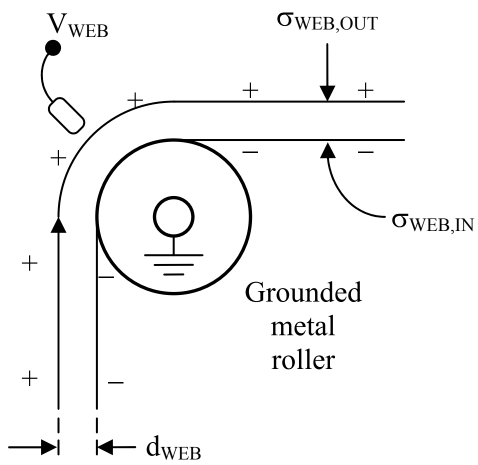


Figure 6: A non-contacting electrostatic voltmeter measures the surface potential V_{WEB} of the web wrapped on a grounded metal conveyance roller. V_{WEB} varies only with the surface charge density $\sigma_{WEB,OUT}$ on the exposed surface of the web.

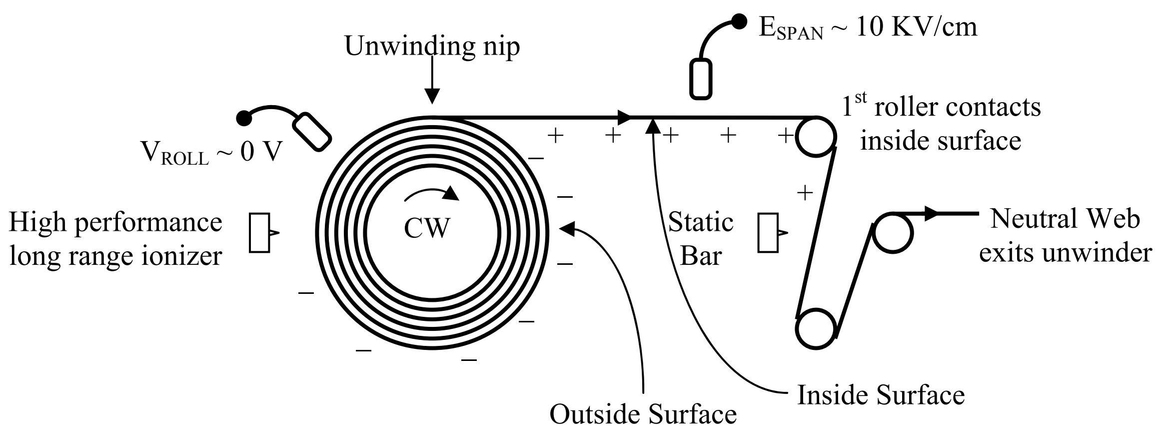
3. NEUTRALIZING STATIC CHARGE ON UNWINDING ROLLS

Static on the unwinding roll in Figure 7 is effectively neutralized using 2 ionizers; a high performance, long range ionizer and a traditional AC static bar. A high performance, long range ionizer must be used to neutralize the outside surface of the unwinding roll because the distance from the ionizer to the roll increases as the unwinding roll expires. Also, the unwind geometry is often complex and congested. The unwinder may be a turret with several spindles as in Figure 8. A crane is often used to lift rolls and the ionizers must be located so that they do not interfere with roll handling. The unwind geometry may require that the high performance ionizer be located some distance from the unwinding roll.

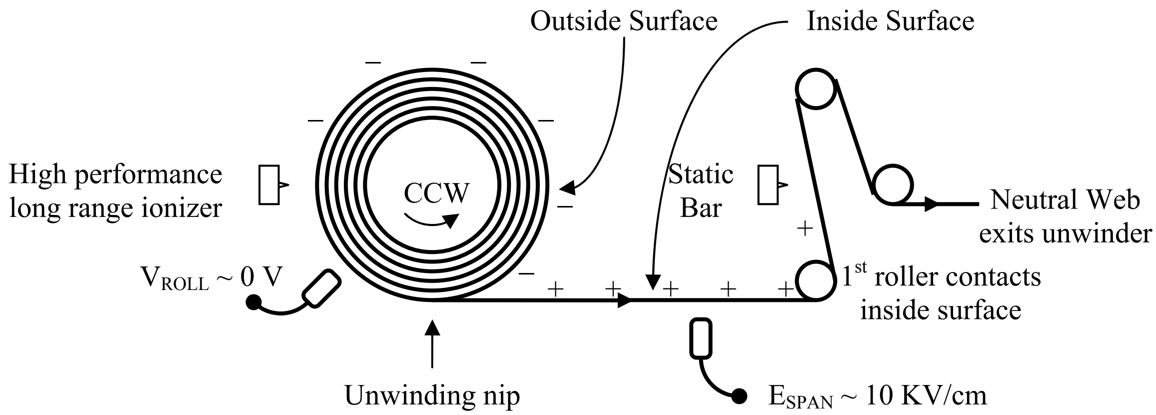
The role of the high performance, long range ionizer is to neutralize the charge on the outside surface of the unwinding roll, which is negative in Figure 7. The effectiveness of the high performance ionizer may be verified using two measurements.

1. The voltage V_{ROLL} of the unwinding roll should be nearly zero.
2. The electric field E_{SPAN} on the span from the unwinding roll to the first roller should be very high; 10 KV/cm or higher.

A second static bar is used to neutralize static charge on the inside surface of the web. This ionizer could be located along the web span from the unwinding roll to the first roller. However, the location of this span varies as the roll expires, and the performance of static bars varies with the distance to the web. The geometry of this span is often complex. For example, with a rotating turret in Figure 8, the position of this first span varies by several roll diameters. During turret rotation, the span exiting the unwinding roll contacts an additional conveyance roller. In Figure 8, static bar SB3 that neutralizes the inside web surface is located on the span between roller 3 and roller 4. Here, the spacing between static bar SB3 and the web is fixed. In addition, this location is often much more accessible for ionizer maintenance and cleaning.



(a) Shown is the thread-up for a clockwise or over unwind.

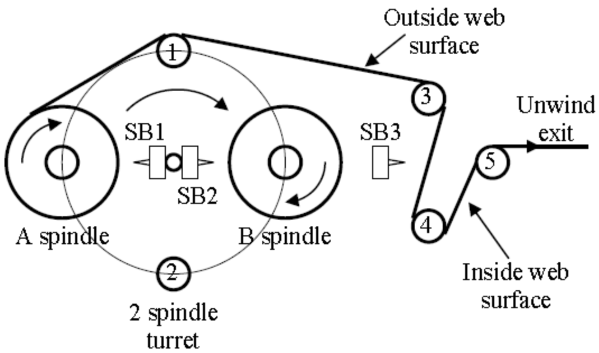


(b) Shown is the thread-up for a counter-clockwise or under unwind.

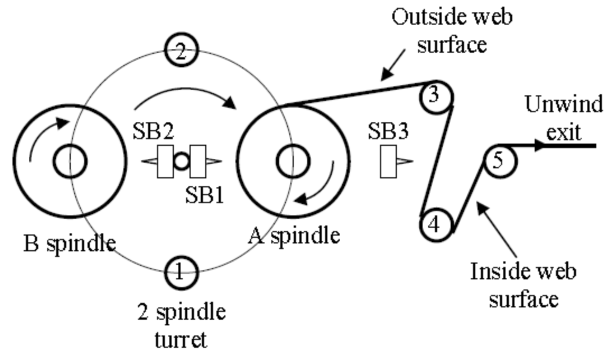
Figure 7: A high performance, long range ionizer neutralizes the charge on the outside surface of the unwinding roll. A static bar after the first conveyance roller neutralizes the charge on the inside web surface. The web exiting the unwinder is nearly electrically neutral.

The locations of the rollers between the unwinding roll and the static bar that neutralizes the inside surface of the web are critical. As shown in Figure 7, the web along the spans between the unwinding roll and static bar that neutralizes the inside web surface will have high static. The high static on the web in Figure 9(a) generates an electrical discharge in the gap between the web and the roller surface just before the web touches the roller; pre-nip ionization. Ions of both polarities are generated. Negative ions are attracted to the web, which partially neutralizes the charged, inside surface. Positive ions move towards the grounded roller. The result is that the web exiting contact with the first roller is partially neutralized. The static bar located past the rollers that touch only the inside web surface neutralizes the charge remaining on the inside web surface.

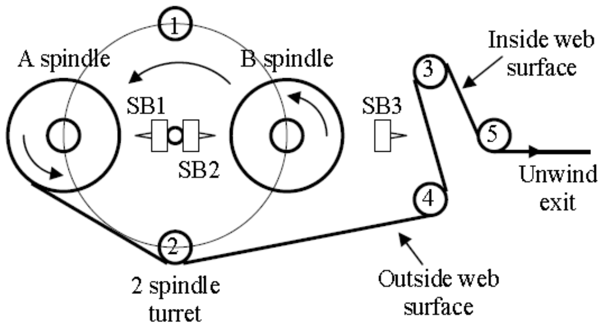
The location of the conveyance roller in Figure 9(b) improperly contacts the neural outside web surface. The high static on the web generates pre-nip ionization. Ions of both polarities are generated. Negative ions are attracted towards the web, which partially charges the previously neutral surface. Positive ions move towards the grounded roller. The web exiting contact with the first roller now has charge on both sides. The static bar located just downstream of the first roller neutralizes the charge remaining on the web. The result is that the web has positive charge on the inside surface and an equal amount of negative charge on the outside surface. The performance of the static neutralization system has been compromised.



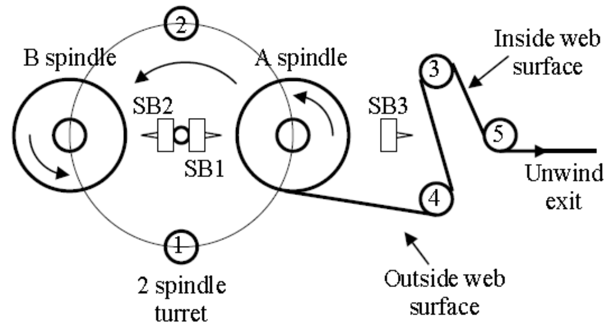
(A) With a clockwise unwind from spindle A, the inside web surface touches both rollers 1 and 2 prior to being neutralized by static bar SB3.



(B) With a clockwise unwind from spindle A, after the turret rotates the inside web surface touches only roller 3 prior to being neutralized by static bar SB3.



(C) With a counter clockwise unwind from spindle A, the inside web surface touches both rollers 2 and 4 prior to being neutralized by static bar SB3.



(D) With a counter clockwise unwind from spindle A, after the turret rotates the inside web surface touches only roller 4 prior to being neutralized by static bar SB3.

Figure 8: On a 2-spindle turret, the high performance, long range static bars SB1 and SB2 that neutralize the outside surfaces of the webs on the unwinding rolls are located on the axis of the turret. All conveyance rollers from the unwinding roll to static bar SB3 touch only the inside web surface. The web exiting the unwinder is nearly electrically neutral.

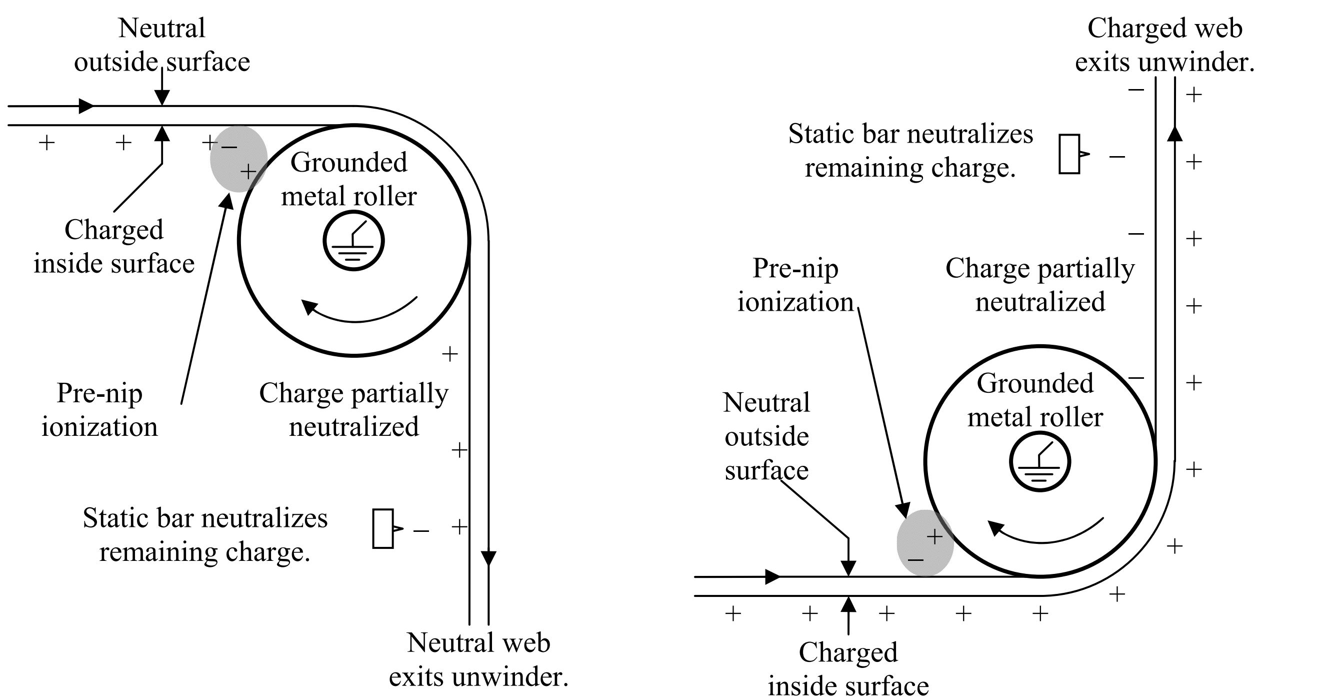
SUMMARY

1) Each time a roll is unwound is a unique opportunity to neutralize static.
2) Two common root causes of static on the unwinding roll are:
   i) tribocharging between the inside surface and the outside surface at the unwinding nip, and
   ii) charge that has accumulated on the web from previous operations where one side has positive charge and the other side has an equal amount of negative charge.
3) While static charges on the unwinding roll from these two root causes are identical and indistinguishable, their countermeasures are quite different.
4) Tribocharging is minimized by adjusting the product formulation.
5) Static that accumulates from previous operations is neutralized by the static control system installed along the conveyance path.

6) The static neutralization method for the unwinding roll has three key elements:
   a) A high performance static bar neutralizes static on the outside surface of the unwinding roll.
   b) A static bar neutralizes static on the inside surface of the web. This bar should be located prior to the first conveyance roller that touches the outside web surface.
   c) One or more conveyance rollers from the unwinding roll to the static bar that neutralizes the inside web surface must touch only in inside web surface.

7) The conveyance rollers between the unwinding roll and the static bar that neutralizes the inside web surface must contact only the inside web surface. Pre-nip ionization at these rollers will partially neutralize the charged inside web surface.

8) Charge neutralization performance is compromised if any conveyance rollers prior to the static bar that neutralizes the inside web surface contacts the outside web surface.



(a) An electrically neutral web exits the unwinder when the first roller touches the inside surface.

(b) An electrically charged web exits the unwinder when the first roller touches the outside surface.

Figure 9: Pre-nip ionization occurs in the air gap between the charged web and the roller prior to contact. Here, pre-nip ionization deposits negative charge on the web surface that touches the roller.

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