Effectiveness of Covered Conductors: Failure Mode Identification and Literature Review

Effectiveness of Covered Conductors: Failure Mode Identification and Literature Review

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Executive Summary

Exponent, Inc. (Exponent) was jointly retained by the California investor-owned utilities (IOUs) to assess the effectiveness and reliability of covered conductors (CCs) for overhead distribution system hardening. Our investigation included a literature review, discussions with subject matter experts, a failure mode identification workshop, and a gap analysis comparing expected failure modes to currently available test and field data. Based on our investigation to date, we offer the following conclusions:

1. Covered conductors are a mature technology (in use since the 1970s) and have the potential to mitigate several safety, reliability, and wildfire risks inherent to bare conductors. This is due to the reduced vulnerability to arcing/faults afforded by the multi-layered polymeric insulating sheath material.

2. A subject matter expert workshop, composed of six California IOUs and Exponent, was conducted, and identified hazards and failure modes affecting bare conductors and CCs. Of the 10 hazards that affect bare conductors, CCs have the potential to mitigate six. Mitigated hazards include tree/vegetation contact, wind-induced contact (such as conductor slapping), third-party damage, animal-related damage, public/worker impact, and moisture.

3. The primary failure mode of bare conductors is arcing due to external contact. Laboratory studies and field experience have shown that arcing due to external contact was largely mitigated with CCs. Therefore, a corresponding reduction in ignition potential would be expected.

4. Field experience from around the world, including North America, South America, Europe, Asia, and Australia, consistently report improvements in reliability, decreases in public safety incidents, and decreases in wildfire-related events that correlate with increased conversion to CC.

5. While high-level field experience–based evidence of CC effectiveness is plentiful, relatively few lab-based studies exist that address specific failure modes or quantify risk reduction relative to bare conductors. For some failure modes, further testing is recommended to bolster industry knowledge and to enable more effective risk assessment.

6. Several CC-specific failure modes exist that require operators to consider additional personnel training, augmented installation practices, and adoption of new mitigation strategies (e.g., additional lightning arrestors, conductor washing programs, etc.).

Note that this Executive Summary does not contain all of Exponent's technical evaluations, analyses, conclusions, and recommendations. Hence, the main body of this report is at all times the controlling document.

Motivation and Scope

California investor-owned utilities (IOUs) Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) engaged Exponent to summarize the effectiveness of CCs for hardening of overhead distribution electric lines. During the project, three additional California IOUs joined the effort: Liberty, PacifiCorp, and Bear Valley Electric Service. CCs have gained industry attention due to their potential for mitigating risks associated with public safety, reliability, and wildfire ignition. The current study was undertaken to better understand the advantages, operative failure modes, and current state of knowledge regarding CCs. The objectives of this study were to:

1. Summarize the effectiveness of CCs.
2. Summarize the implementation and design considerations of CCs.
3. Identify gaps in current testing/knowledge and practices/implementation.

To meet these objectives, we performed a comprehensive review of publicly available literature, utility-provided data, and manufacturer information. Additionally, a high-level failure mode identification workshop was conducted with input from technical subject matter experts representing the California IOUs and Exponent. The workshop output was compared against the available literature and test data to identify any gaps between the current state of knowledge and the identified failure modes.

Covered Conductor Technology

History and Motivation for Development

The term “covered conductor” refers to a variety of conductor cable designs that incorporate an external polymer sheath to protect against incidental contact with other conductors or grounded objects such as tree branches. This technology has several advantages over traditional bare conductors, and the key drivers for adoption have been to improve overall system reliability, to enhance public safety in high-population areas, to decrease required right-of-way in densely forested areas, to decrease the scope and frequency of vegetation management, and to reduce the probability of ignition from conductor heating/arcing in fire-prone areas.

Construction and Types

CCs were first adopted in the United States and Europe in the 1970s for medium-voltage distribution lines (35 kV and below) and were later implemented for high-voltage overhead lines in the 1990s [Leskinen 2004]. Early iterations had various technical challenges that led to the development of the modern CC design that will be discussed throughout this report. Modern CCs consist of an all-aluminum conductor (AAC), aluminum conductor with steel reinforcement (ACSR), or copper (CU) conductor, enclosed in a multi-layer polymer sheath. The number of layers and their composition largely depend on the specified voltage rating, as multi-layered variants have a higher impulse strength than the single-layer design and often include a semiconducting conductor shield. This report focuses on CC use in the “medium voltage” range (6–35 kV), though the technology can also be used for higher or lower voltage.

Figure 1 shows a three-layer CC design, which is commonly used for distribution-level voltages. A high-density polyethylene (HDPE) outer jacket provides strength, abrasion resistance, and weather resistance. This layer may be cross-linked to increase its high temperature strength and dimensional stability. A low-density polyethylene (LDPE) inner jacket provides dielectric strength to protect the underlying conductor and may also be cross-linked to enhance high temperature properties. Finally, a semiconducting thermoset “shield” layer is wrapped around the conductor, which equalizes the electric field around the conductor to reduce voltage stress and preserve the insulation [Wareing 2005].

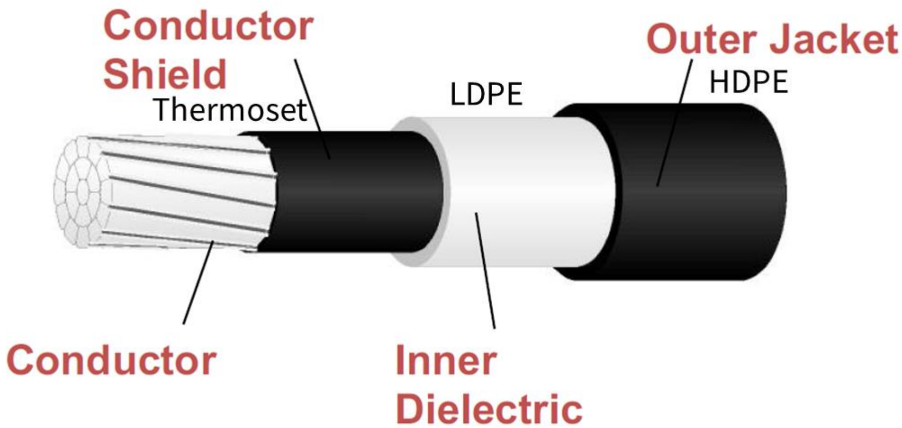


Figure 1. A schematic illustration of a three-layer CC. Diagram modified from Hendrix Aerial Cable Systems [Trager].

Overhead Configurations

One common configuration for CCs used in overhead distribution systems is the standard crossarm-mounted construction. This configuration, sometimes referred to as "tree wire," is often seen where CCs are installed on pre-existing infrastructure designed for bare conductors. This method can leverage legacy hardware, construction and maintenance practices, and pole structures if the weight, diameter, and modified tensioning are considered. Conductors are typically attached to polyethylene pin-type insulators in this configuration. A reduced crossarm structure can also be used in narrow rights-of-way. One disadvantage to this method of installation is that it requires stripping of the conductor sheath at dead-end attachments, creating a length of unprotected bare conductor. Figure 2 shows an example of tree wire construction.

Figure 2. An example of crossarm-mounted CC, or “tree wire,” construction. Photo from Hendrix Aerial Cable Systems [Trager].

CCs are also often constructed in a “spacer cable” configuration. Spacer cable takes advantage of the reduced clearance required of CCs by closely spacing adjacent conductor phases with rigid spacer hardware. This configuration is advantageous in tight corridors where right-of-way may be limited and can reduce wind-related impact on individual conductors [Trager]. No stripping of the conductor sheath is required for this installation method, resulting in a completely covered system except for tap, transformer/capacitor, surge arrester, and protective device locations. A notable feature of spacer cable is that the conductor is not self-supporting, but rather, a steel cable or “messenger cable” is used to support multiple conductors. The messenger cable can also shield the conductors somewhat from fallen branches and lightning strikes. Figure 3 shows an example of spacer cable construction.

Figure 3. An example of spacer cable CC construction. Photo from Hendrix Aerial Cable Systems [Trager].

Field Experience

Finland

Finland started adopting CCs for medium-voltage lines in the 1970s and high-voltage lines in the 1990s to increase reliability. While only 4% of the total medium-voltage network, CCs accounted for 90% of the total average medium-voltage length increase during the early 2000s [Leskinen 2004].

The annual outage rate per 100 km from Finland is shown in Figure 4 and is valid for rural areas. As the figure shows, the number of faults has steadily decreased since the 1970s to around five faults per 100 km. This likely corresponds to the increased number of CC lines in the network [Leskinen 2004].

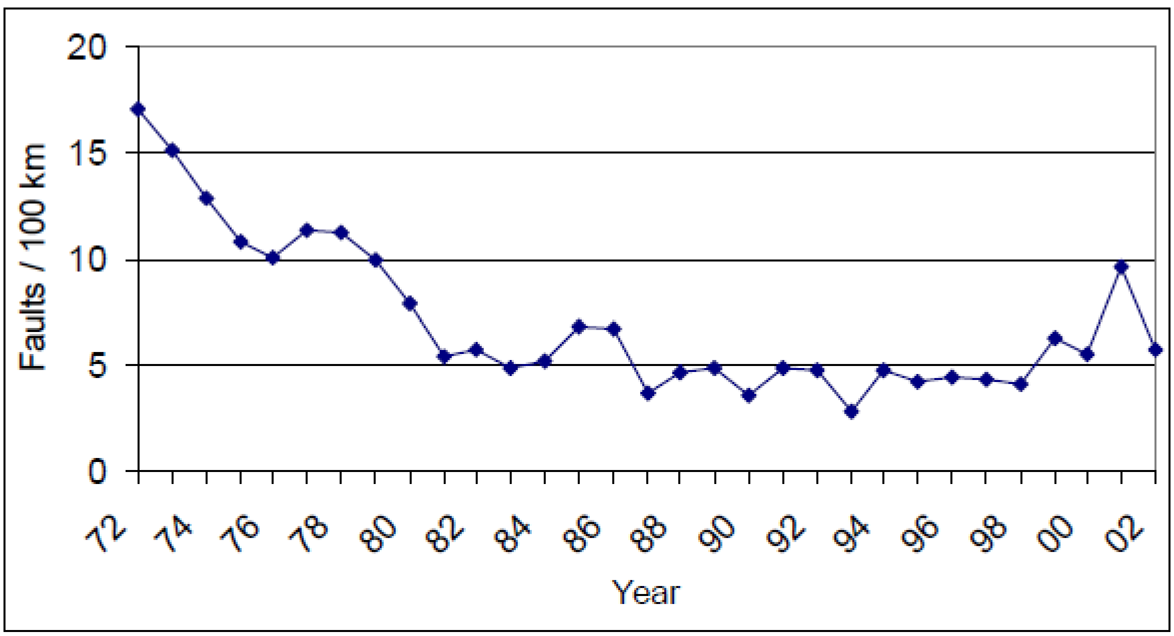


Figure 4. Annual number of faults per 100 km in rural areas of Finland from 1972 to 2002 for medium-voltage lines. Image from [Leskinen 2004].

This study also analyzed previous literature that suggested CC installation also affects the number of high-speed and delayed automatic reclosings. Based on the field data-derived empirical equations from Heine, *et. al*., as shown in Figure 5, the number of high-speed autoreclosings decreases by one third when the percentage of CC lines increases from 10% to 50% [Heine 2003, Leskinen 2004]. The number of autoreclosings is indicative of the number of faults; therefore, these data suggest that the number of faults decreased with increased use of CCs. More recent studies show that the number of permanent faults in CC lines is 20% of the number associated with bare conductor overhead lines and gives an annual fault number of one per 100 km [Leskinen 2004].

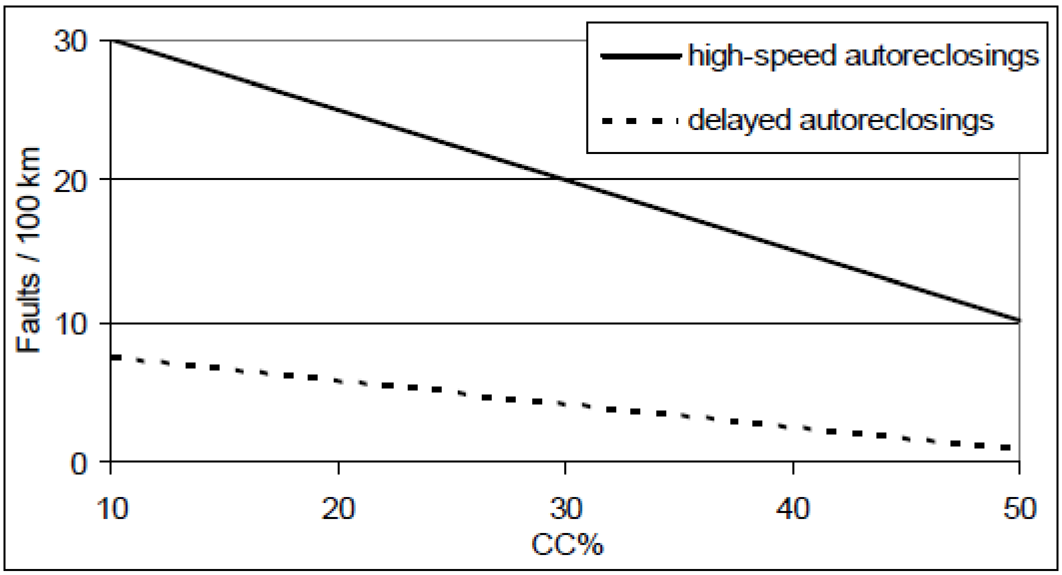


Figure 5. Fault frequency as a function of CC network share in Finland. Image from [Leskinen 2004].

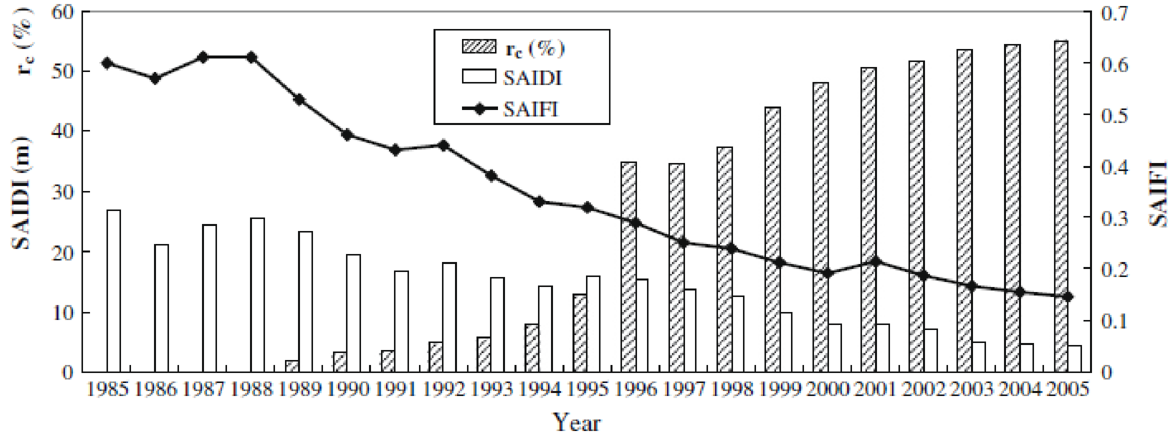
Slovenia

The Slovenian utility Elektro Ljubljana began building CC lines in 1993 to improve reliability, and within ten years CC lines comprised 8% of all Slovenian medium-voltage overhead lines [Leskinen 2004]. The annual medium-voltage outage rate in rural Slovenia was between 15 and 25 per 100 km prior to the introduction of CCs. After the adoption of CC lines and other new technology such as remote-controlled load breakers and shunt circuit breakers, the annual outage rate reduced to less than two faults per 100 km. This rate is nearly double the most recent annual outage rate of Finland, as discussed in the prior section. The higher fault rate in Slovenia compared to Finland has been attributed to the higher level of lightning and a lack of standards [Leskinen 2004].

Taiwan

The Taiwan Power Company invested the equivalent of over $360 million between 1996 and 2000 to replace 11.4 kV overhead lines with 15 kV cross-linked polyethylene (XLPE) weatherproof wires (a type of CC) [Li 2010]. Figure 6 shows the impact of CC lines on the Taiwan Power Company distribution system. (The ratio of covered line length using XLPE weatherproof wire in the distribution system to the total line length of the system is given by the variable r_c.) The distribution system reliability is assessed using the system average interruption frequency index (SAIFI) and the system average interruption duration index (SAIDI). Figure 6 shows the variation of r_c, SAIFI, and SAIDI during 1985 to 2005. Installation of CC lines from 1985 to 2005 resulted in lower fault frequency and interruption duration.

As distribution systems in Taiwan are near highly populated areas, endangered-life indices (ELIs) were used for statistical data with regard to people who experience electric shocks. The following ELI values were used: the annual number of people who receive electric shocks (N_p), the annual number of people injured by electric shocks (N_{pi}), and the annual number of people electrocuted (N_{pe}). The ELI rates and r_c values from 1985 to 2005 are shown in Figure 6. As r_c increased, all ELIs decreased annually from 1995 to 2005 as more CC lines were incorporated into the distribution system.



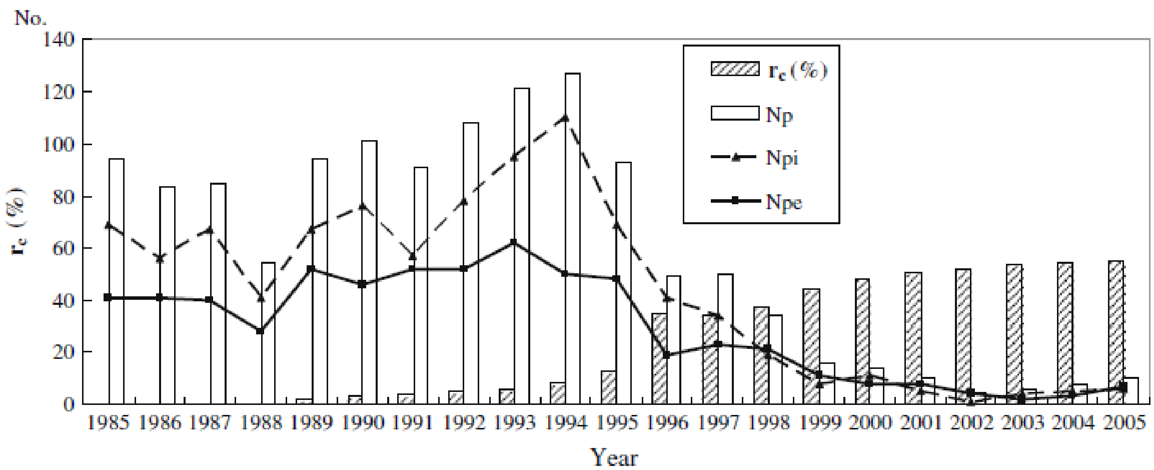


Figure 6. (Top) Taiwan Power Company results from 1985 to 2005 for the ratio of covered line length using XLPE weatherproof wire in a distribution system to the total line length of the system (r_c), system average interruption frequency index (SAIFI), and the system average interruption duration index (SAIDI). (Bottom) Taiwan Power Company results from 1985 to 2005 r_c and endangered-life indices (ELIs). The following ELI values are shown: annual number of people who receive electric shocks (N_p), annual number of people injured by electric shocks (N_{pi}), and annual number of people electrocuted (N_{pe}). Image from [Li 2010].

Australia

CCs have been used in Australia for more than 50 years, primarily motivated by wildfire risk reduction. Early CCs had limited lifetimes due to surface degradation, tracking, radio frequency (RF) emissions, and lightning damage [Wareing 2005]. In the mid-2000s, the Australian Strategic Technology Program determined that technological advancements may help solve historical issues with CCs to allow for their widespread adoption. After the Black Saturday bushfires, the Victorian Bushfires Royal Commission (VBRC) recommended the existing power lines be replaced with aerial bundled cables or other technology that reduced the risk of bushfires. The VBRC estimated a 90% reduction in the likelihood of a bushfire starting by installing CCs [SCE 2019]. Additionally, a study by the Commonwealth Scientific and Industrial Research Organization (CSIRO) found that a 98% reduction in the risk of bush fires due to CCs could be expected [SCE 2019, Electrical Connection 2021]. Although it is unclear how these specific metrics were determined, this shows high confidence by the VBRC and the CSIRO in the effectiveness of CC for wildfire mitigation.

Malaysia

The Tengag Nasional Berhad (TNB) distribution network in Malaysia includes 5,300 km of 33 kV, 22 kV, and 11 kV medium-voltage bare overhead conductor lines and 2,700 km of 33 kV and 11 kV medium-voltage aerial-bundled cables (ABC) lines [Ariffin 2012]. Malaysia has reliability challenges caused by above-average lightning activity, small-animal damage, and vegetation damage, which motivated the use of CCs to improve reliability. TNB started installing medium-voltage ABC lines in the 1990s. Early versions of ABCs had inferior fault rates and failed to deliver on the expected benefits. A redesign was undertaken to change from the single-layer copper screen with HDPE outer sheath to a double-layer copper screen. Additionally, improved construction standards were followed, and compatible accessories were used that resulted in improved performance.

TNB found that the medium-voltage bare conductor lines had a higher number of recorded failures compared with medium-voltage ABC lines from 2001 to 2007. The newly designed medium-voltage ABCs had a failure rate five times lower than that of the original medium-voltage ABCs used in the Malaysian system. In this study, a specific definition for the word “failure” was not provided.

Brazil

CEMIG, one of the four biggest power companies in Brazil, adopted spacer cables in urban areas starting in 1998 to improve reliability [Rocha 2000]. CEMIG's annual work plan was to rebuild the urban distribution system by building 1,400 km of medium-voltage lines and 2,800 km of low-voltage lines using spacer cables. CEMIG completed periodic field inspections during the first nine years of energizing the initial pilot lines. The following observations were made during the field inspections:

- Outages due to atmospheric discharges were observed where the cables had been peeled to create a metallic tie. Changes were made to how ties, polymeric rings, and polymeric anchoring clamps were installed, which resulted in improved performance.
- In areas with permanent tree contact, no signs of electrical tracking were observed.
- Minimal outages were observed in areas with vandalism (insulator breakage) and pole collisions. No outages were recorded on spacer cable lines with vandalism incidents, whereas four to five outages occurred on bare cable lines.
- Outages caused by material failures were practically eliminated.

Overall, CEMIG found a 33% reduction in the average duration and frequency of outages per customer due to the expansion of spacer cable lines [Nishimura 2001].

Failure Modes and Effectiveness

Failure Modes

A high-level failure mode identification workshop was conducted to identify operative failure modes relevant to overhead distribution systems for both bare conductors and CCs. The list of failure modes was developed during a day-long workshop with technical subject matter experts representing Exponent, PG&E, SCE, SDG&E, PacifiCorp, Liberty, and Bear Valley Electric Service. This exercise leveraged the technical knowledge from the seven different organizations and the combined experience and shared operator experiences from the six utilities. This workshop was not a full risk assessment, as other factors such as severity / consequence of an event, likelihood, and ability to detect each failure mode were outside the scope of this exercise.

The output of the failure mode workshop was a list of failure modes applicable to bare conductors and/or CCs and is presented in Table 1. The failure modes are organized into three descriptive categories: external events, human factors, and operations/maintenance. Each line item is further differentiated by the operative hazard within each category. External events primarily include hazards related to weather, vegetation, or fire. Human factors include human-induced hazards such as vehicle/equipment contact, gunshots, and Mylar balloons. The operations/maintenance category encompasses hazards related to the design, installation, and maintenance of overhead distribution lines. Within each hazard, specific scenarios that can result in failure are listed. For example, a phase-to-phase fault (failure mode) resulting from a Mylar balloon (hazard) is differentiated from a phase-to-phase fault (failure mode) resulting from a fallen tree branch (hazard). Failure modes that apply to bare conductors but are largely mitigated by using CCs are marked with a green checkmark.

Table 1. List of failure modes for bare and covered conductors.

Category	Hazard	Scenario	Bare	Covered	#	Failure Mode
External Events	Fire	External fire (wildfire)		X	1	Potential damage to sheath, reducing effectiveness
				X	2	Potential flammability of CC sheath
			X	X	3	Annealing of metal conductor due to fire exposure
External Events	Extreme heat	Extreme temperatures cause sag and clearance issues	X	✓	4	Phase-to-phase or phase-to-ground fault
External Events	UV exposure / solar exposure	Aging / exposure of conductor covering		X	5	Embrittlement and/or cracking of conductor covering
External Events	Sheath contamination	Moisture / salt contamination		X	6	Tracking/insulation failure due to moisture/salt (corona)
		Smoke during fire		X	7	Tracking/insulation failure due to smoke/ash
External Events	Ice/snow	Mechanical loading / stress on conductors	X	X	8	Excessive mechanical loading leading to conductor failure/wire down
		Unloading / dynamic shedding of ice	X	X	9	Dynamic forces leading to conductor failure and wire down
		Combined wind/ice	X	X	10	Galloping (see wind hazard)
External Events	Lightning	Atmospheric lightning	X*	X	11	Arc damage / melting of conductor, possible wire down. Short circuit duty exceeds conductor damage curve.
External Events	Animal	Animal contact		X	12	Phase-to-phase fault due to animal-damaged sheath (chewing)
				X	13	Bird dropping degradation of polymer sheath
			X	✓	14	Large bird contact of multiple conductors (phase-to-phase)

Category	Hazard	Scenario	Bare	Covered	#	Failure Mode
External Events	Moisture	Moisture/salt/ oceanic exposure	X	✓	15	Atmospheric corrosion of span leading to decreased mechanical strength or increased electrical resistance
			X	X	16	Atmospheric corrosion near hardware/dead-end leading to decreased mechanical strength or increased electrical resistance
				X	17	Freeze/thaw cycles leading to sheath damage
			X	X	18	Lack of corrosion inhibitors (on splices) leading to corrosion
				X	19	Migration of water within the sheath layer
			X	✓	20	Stress corrosion cracking of span
			X	X	21	Stress corrosion cracking near hardware/dead-end
External Events	Wind	Winds (within the natural frequency of structure)	X	X	22	Aeolian vibration-induced fatigue cracking
			X	X	23	Mechanical overload of tie wire during galloping (ice/ or lashing of spacer /messenger wires)
			X	X	24	Swinging leading to wear
			X	X	25	Vortex shedding impact / contact of adjacent conductors leading to fatigue of downstream conductors
			X	✓	26	Line slapping (intermittent conductor contact)
		Transmission / distribution line contact	X	✓	27	Differential wind-driven blowout leading to contact of distribution / transmission lines
		Pole damage		X	28	Damage due to potential for increased loading when new covered conductors replace existing bare conductors on the same poles / crossarms / guys

Category	Hazard	Scenario	Bare	Covered	#	Failure Mode
External Events	Tree damage	Tree falls, breaks conductor	X	✓	29	Conductor failure / wire down resulting in loss of service, potential for ignition (along the entire length of bare conductor or exposed section of CC)
			X	X	30	Live conductor down with no outage
		Tree branch bridges various lines (conductors do not break)	X	✓	31	Phase-to-phase fault, potential ignition
			X	X	32	Delayed fault due to long-term contact (dielectric breakdown / reduction in dielectric strength), potential phase-to-phase fault
				X	33	Abrasion of sheath
				X	34	Cracking of CC sheath
				X	35	Heating damage to sheath
				X	36	Corrosion of conductor due to compromised sheath
		Tree falls and pulls entire system to ground	X	X	37	Surrounding structure fails (broken conductor)
			X	X	38	Surrounding structure fails (conductor intact)
Human Factors	Public/worker impact	Agricultural equipment / third-party workers / under-build workers (cable/telephone)	X	✓	39	Potential for shock or electrocution
		Vehicle impact to pole / guy wire	X	✓	40	Potential for guy wire whip to create contact to conductor
			X	✓	41	Phase-to-phase contact
			X	✓	42	Phase-to-ground contact
		Gunshots	X	X	43	Conductor damage

Category	Hazard	Scenario	Bare	Covered	#	Failure Mode
Human Factors	Third-party damage	Tarps under high wind conditions	X	✓	44	Phase-to-phase contact
		Balloons	X	✓	45	Phase-to-phase contact
		Kites	X	✓	46	Phase-to-phase contact
		Palm fronds	X	✓	47	Phase-to-phase contact
Operations & Maintenance	Maintenance / Installation	Conductor damage due to incorrect hardware tool or incorrect stripping		X	48	Mechanical damage to sheath (dent/gouge)
		Poor splicing or poor connection	X	X	49	Poor contact leading to localized heating and connection failure
		Over-tensioning	X	X	50	Incorrect tensioning leading to conductor failure (due to vibration, increased stress)
		Under-tensioning	X	X	51	Increased sway leading to wear
			X	✓	52	Clearance issues due to increased sway
		Excessive angles	X	X	53	Insulator breaks off due to mechanical overload (for excessive angles). Conductor may break off or float, contacting pole.
		Broken tie wires	X	X	54	Poorly installed tie wires could break, leading to conductors separating from insulators and contacting pole.
		Improper installation	X	X	55	Bird caging—conductor strands separate

* Direct lightning strikes resulting in concentrated heating of the bare conductor and a wire down event are relatively infrequent.

Effectiveness of Covered Conductors

Failure Mode Discussion

In total, 58 unique failure mode / hazard scenario combinations were identified through the failure mode workshop. These failure modes can be categorized into three basic types:

1. Failure modes that affect both bare *and* CCs.

   Example: Aeolian vibration-induced fatigue cracking of the metal conductor (Table 1, No. 23).
2. Failure modes that affect bare conductors but are reduced or effectively eliminated by CCs.

   Example: Phase-to-phase fault due to tree branch bridging conductor phases (Table 1, No. 32).
3. Failure modes that are unique to CCs that do *not* affect bare conductors.

   Example: Lightning-induced melting of conductor sheath (Table 1, No. 12).

Failure modes that apply to bare and covered conductors

Failure modes that apply to both bare and covered conductors are well known due to historic use of bare conductors and are generally expected to be effectively managed through existing mitigations and controls. However, there are instances in which these failure modes may be *more* prevalent with CCs than with bare conductors. For instance, some wind-related phenomena such as Aeolian vibration may, in certain circumstances, be exacerbated with CCs due to their smooth surface, increased weight, and larger overall diameter [Leskinen 2004]. For similar reasons, CCs may also be more prone to ice loading than bare conductors. Ice loading may result in mechanical overload of the conductor, or increased susceptibility to galloping. A full list of failure modes that apply to both bare and covered conductors derived from the failure mode workshop is given in Table 2.

Table 2. Failure modes that affect both bare and covered conductors.

Hazard	#	Failure Mode	Potential risk relative to bare
Fire	3	Annealing of metal conductor due to fire exposure	Reduced
Ice/snow	8	Excessive mechanical loading leading to conductor failure / wire down	Increased
	9	Dynamic forces (ice shedding) leading to conductor failure and wire down	Needs study
	10	Galloping damage (see wind scenario)	Needs study
Lightning	11	Arc damage / melting of conductor, possible wire down	Increased
Moisture	16	Atmospheric corrosion near hardware/dead-end leading to decreased mechanical strength or increased electrical resistance	Comparable
	18	Lack of corrosion inhibitors (on splices) leading to corrosion	Comparable
	21	Stress corrosion cracking near hardware/dead-end	Comparable
Wind	22	Aeolian vibration induced fatigue cracking	Needs study
	23	Mechanical overload of tie wire during galloping (ice/ or lashing of spacer /messenger wires)	Needs study
	24	Swinging leading to wear	Increased
	25	Vortex shedding impact / contact of adjacent conductors leading to fatigue of downstream conductors	Needs study
Tree damage	30	Live conductor down with no outage	Increased
	32	Delayed fault due to long-term contact	Reduced
	37	Surrounding structure fails (broken conductor)	Needs study
	38	Surrounding structure fails (conductor intact)	Needs study
Third-party damage	43	Conductor damage from gunshot	Comparable
Maintenance/ installation	49	Poor contact leading to localized heating and connection failure	Comparable
	50	Incorrect tensioning leading to conductor failure (due to vibration, increased stress)	Comparable
	51	Increased sway leading to increased wear	Needs study
	53	Insulator breaks off due to mechanical overload (for excessive angles). Conductor may break off or float contacting pole.	Comparable
	54	Poorly installed tie wires could break, leading to conductors separating from insulators and contacting pole.	Comparable
	55	Bird caging—conductor strands separate	Comparable

These failure modes that can affect both bare and covered conductors are of particular importance to operators, as risk assessments may need to be updated to reflect the increased likelihood of certain events when switching to CCs. Since no studies were found that directly compared the frequency or severity of these failure modes between covered and bare conductors, the impact on mitigation and maintenance practices has not been quantified.

Despite the dearth of test data on the likelihood and severity of these failure modes for CCs relative to bare conductors, insight can be gained from a first-principles analysis of these failure modes. For example, the vulnerability to fatigue from Aeolian vibration is expected to be different for CCs for several reasons. The Aeolian vortex shedding frequency is inversely proportional to transverse wind speed, and therefore the shedding frequency will be lower for CCs because of the increase in conductor diameter due to the insulation. However, this lower cycle count could be offset by differences in the wind power input of self-damping, which define the vibration amplitude. In addition, Aeolian fatigue failure typically manifests at attachments (clamps), and it is not known whether typical CC connectors are more susceptible to the strain concentrations that lead to failure. Similarly, ice gravity loading and dynamic loads from ice and snow shedding can be expected to differ due to different conductor diameter, surface roughness, weight, and surface temperature. Additional analysis is required to better understand these failure modes.

Failure modes mitigated by covered conductors

The next group of failure modes are those that are largely mitigated by the use of covered conductors. These failure modes are the primary drivers for adoption of CCs, as they represent the risk reduction potential compared to traditional bare conductors. A total of 17 failure modes largely mitigated through the use of CC were identified through the workshop exercise, and are marked with a green checkmark in Table 1. The common theme among these failure modes is that they are created through contact with third-party objects, vegetation, or other conductors that create phase-to-ground or phase-to-phase faults. The available literature, industry testing, and field experiences from utilities around the world suggest that modern CCs can prevent arcing in the medium-voltage range over short time scales, thereby increasing system reliability and public safety, and reducing the potential for wildfire ignition. A full list of failure modes addressed by CCs derived from the failure mode workshop is given in Table 3.

Table 3. Failure modes that affect bare conductors but are largely mitigated by covered conductors.

Hazard	#	Failure Mode
Extreme heat	4	Fault due to sag/clearance issues
Animal	14	Large bird contact of multiple conductors (phase-to-phase contact)
Moisture	15	Atmospheric corrosion of span leading to decreased mechanical strength or increased electrical resistance
	20	Stress corrosion cracking of span
Wind	26	Line slapping (intermittent conductor contact)
	27	Differential wind driven blowout leading to contact of distribution / transmission lines
Tree damage	29	Conductor failure/wire down resulting in loss of service, potential for ignition (along the entire length of bare conductor or exposed section of CC)
	31	Phase-to-phase fault. Potential ignition.
Public/worker impact	39	Potential for shock or electrocution
	40	Potential for guy wire whip to create contact to conductor
	41	Phase-to-phase contact (vehicle)
	42	Phase-to-ground contact (vehicle)
Third-party damage	44	Phase-to-phase contact (tarp)
	45	Phase-to-phase contact (balloon)
	46	Phase-to-phase contact (kite)
	47	Phase-to-phase contact (palm frond)
Maintenance/ Installation	52	Clearance issues due to increased sway

As stated above, these failure modes generally consist of arcing between phases or objects. The primary and secondary effects of these failure modes have implications for system reliability, public safety, and wildfire prevention. For example, arcing between phases due to conductor slapping can create sparks, conductor melting, and/or a possible wire-down scenario. This not only creates an outage risk but also creates potential for a wildfire ignition if dry brush exists below the lines. As will be discussed, available literature indicates that CCs prevent arcing during line slap, such that sparks and melting never occur. In another example, windstorms can blow debris and vegetation into the conductors. While this may not result in a wire-down event, it can create arcing between phases, and the vegetation (e.g., palm fronds) can ignite and fall to the ground. CCs prevent arcing when vegetation is blown into the lines and, therefore, ignition cannot occur.

The extent to which existing information supports the effectiveness of CCs to address these failure modes was considered. For example, it is generally accepted that CCs largely eliminate the risk of vegetation-caused phase-to-phase faults. However, the literature and existing data were analyzed to understand the extent to which this has been proved and whether there are situations that have not been studied. Testing performed by SCE found that CCs prevented phase-to-phase and phase-to-ground faults in field tests that simulated common scenarios such as branch contact, Mylar balloon contact, and conductor slapping (simulating sustained contact) when energized at 12 kV [SCE 2019]. This is relevant and useful testing, though similar laboratory studies to further bolster these conclusions were not found in the available literature.

Most of the available literature consists of high-level observations that correlate system reliability and safety metrics to increases in CC line installation [Leskinen 2004, Li 2010, SCE 2019, Electrical Connection 2021, Ariffin 2012, Rocha 2000, Nishimura 2001]. These studies suggest that the purported benefits of CCs are effective. However, the benefits are not attributed to specific failure modes, but rather overall system reliability and safety metrics. Further, the true technical limits, i.e., to what extent, and over what time scale arcing is mitigated, still lack concrete data. Few publicly available studies were found that directly test the arcing characteristics of CCs. While the SCE testing provides systematic fault testing of CCs, one limitation of the testing performed by SCE is that it was focused on short-term incidental contact and did not test long-term effects such as a tree branch growing into conductor spans. Second, while the success of these tests at 12 kV provides useful data for many distribution-level applications, an effective steady-state breakdown voltage (upper limit) at which arcing eventually occurs was not identified.

Failure modes unique to covered conductors

Failure modes unique to CCs primarily involve damage or degradation to the insulating polymer sheath. These may not be addressed by mitigations that currently exist under asset management plans geared toward bare conductor use. Therefore, Exponent recommends to better understand these failure modes through available literature and targeted testing. When addressing CC-specific failure modes, it is important to consider that some failure modes may simply reduce the benefits of the covering (i.e., return to bare conductor risk level) while others may create a situation that has a unique and independent risk profile relative to a typical bare conductor installation. These factors will be the focus of the Covered Conductor Risks section below. As will be shown later in the report, some of these failure modes have been largely addressed by advances in technology (e.g., UV stabilizers that reduce embrittlement of conductor covering) or are unlikely to occur (e.g., animal chewing the same spot on two adjacent phases). A full list of the CC-specific failure modes derived from the failure mode workshop is given in Table 4.

Table 4. Failure modes that affect *only* covered conductors.

Hazard	#	Failure Mode
Fire	1	Potential damage to sheath, reducing effectiveness
	2	Potential flammability of CC sheath
UV exposure / solar exposure	5	Embrittlement and/or cracking of conductor covering
Contamination	6	Tracking/insulation failure due to moisture/salt (corona)
	7	Tracking/insulation failure due to smoke/ash
Animal	12	Phase-to-phase fault due to animal-damaged sheath (chewing)
	13	Bird dropping degradation of polymer sheath
Ice/snow	17	Freeze/thaw cycles leading to sheath damage
	19	Migration of water within the sheath layer
Wind	28	Damage due to potential for increased loading when new covered conductors replace existing bare conductors on the same poles / crossarms / guys
Tree damage	33	Abrasion of sheath
	34	Cracking of CC sheaths
	35	Heating damage to sheath
	36	Corrosion of conductor due to compromised sheath

Hazard	#	Failure Mode
Maintenance / installation	48	Mechanical damage to sheath (dent/gouge)

Few published studies were found that analyze specific CC-specific failure modes. However, some data have been obtained from CC manufacturers that assists in understanding the limitations of the technology. Hendrix Wire & Cable has performed several tests on the properties and durability of its CC products. These tests include tracking resistance, ultraviolet (UV) resistance, environmental stress cracking, hot creep tests, and performance of CCs in high-contamination environments [Hendrix 2019, Trager 2006]. These test results suggest that modern CC sheathing is resistant to many forms of environmental degradation. However, since these tests were designed to isolate individual variables in a controlled environment, they do not account for all possible variables in a real-world scenario. The failure modes addressed by the Hendrix testing are likely to reduce the effectiveness of covered conductors but, in most circumstances, would not result in a new, higher-risk profile.

Another consideration that is not represented in the failure mode table is the possibility of undetected wire-down events. The CC sheath provides protection from immediate phase-to-ground faults, and therefore may not trigger fault detection systems. This may lead to high-impedance faults and delay necessary field repairs. Downed bare conductors can also result in high-impedance faults, but the situation will be different for CCs since there will be reduced conductor contact with the ground. The potential for these high-impedance fault events that evade detection is the subject of current research, and new early fault detection systems are in development. Operators transitioning to covered conductors may benefit from further research into early fault detection solutions [SCE 2019, Kistler 2019]. These CC-specific failure modes will be the focus of the Covered Conductor Risks section below.

The failure modes discussed thus far are important for understanding the benefits and tradeoffs of implementing CC technology. The next sections will focus on three broad categories of system performance: reliability, public safety, and wildfire ignition. These sections are structured as such because of the available literature, much of which is not specific to individual failure modes but is broader in nature. Available knowledge in these areas from field experience and lab testing will be highlighted, as well as any deficiencies that may warrant further study.

System Reliability

Industry experience has demonstrated an improvement in system reliability when using CCs [EPRI 2014, Leskinen 2004, Li 2010, Nishimura 2001, Rocha 2000, Ariffin 2012]. The primary driver of this improvement in reliability was the decreased probability of fault events, which resulted in fewer system outages. Finland saw a steady decrease in recorded faults in rural areas in the years after 1972, which corresponded to an expansion of CC use. Finland also found that the number of automatic reclosing events decreased to one third as the percentage of CC lines increased from 10% to 50% [Leskinen 2004]. A Taiwanese study similarly found that SAIFI was reduced by approximately 75% and SAIDI was reduced by approximately 86% as the percentage of CCs was increased from 0% to ~55% [Li 2010]. The Electric Power Research Institute (EPRI) also stated that CCs have the potential to reduce tree-caused outages by 40% based on an analysis of data from Duke Energy and Xcel Energy [EPRI 2015].

Public Safety

Public safety is a driver of CC adoption in high population density areas. The Taiwan Power Company observed a ~92% decrease in the number of people experiencing an electric shock from overhead powerlines from 1994 to 2005, when CCs became nearly 60% of their total distribution network [Li 2010]. Operators in Japan observed a similar correlation between accidents and CC installation, noting a factor of 50% reduction in accidents per year from 1965 to 1984 after converting their entire 74 km 6.6 kV network to CCs [Kyushu 1997]. The National Electric Energy Testing, Research and Applications Center (NEETRAC) at Georgia Tech performed a study on the touch current characteristics of CCs vs. bare conductors [NEETRAC 2018]. Both laboratory testing and computer simulations were performed to investigate the results of human bare-hand contact on a two-mile 12 kV distribution system. These tests demonstrated that the contact current for bare conductor was as high as 7 amperes (A), while the maximum contact current for CCs was in the micro-ampere (μA) range. The increased protection against electric shock incidents is significant. However, damage to the conductor sheath or intentional stripping at hardware or dead-end connections will predictably negate or reduce these benefits.

Wildfire Ignition

Utilities in dry climates such as Australia and the western United States are subject to increased risk of wildfire ignition from powerline failures. The reduced propensity for arcing events with CCs is a distinct advantage for minimizing this risk. The Powerline Bushfire Safety Program of the Victoria, Australia, government commissioned a study that examined the fire performance of CCs in “wire down” ignition tests [Marxsen 2015]. Both covered and bare conductors were tested in “wire on ground” faults under severe fire risk conditions. The authors concluded that intact CCs effectively mitigate ignition risk, stating that “the leakage current through the outer plastic covering with the conductor lying on the ground is not sufficient to create thermal runaway so it does not create fire risk.”

However, tests on damaged CCs, i.e., conductors with existing through-thickness coating loss, found that the probability of ignition for CCs can be higher than with bare conductors due to the concentration of arcing at the damage location. On flat ground with uniform dry grass coverage, the estimated probability of fire ignition for a damaged CC was 67% vs. only 37% for bare conductor [Marxsen 2015]. An important limitation of this test is that it assumes direct contact of the fuel source with the bare portion of the damaged conductor. The probability of fire would likely be much lower in areas with non-uniform vegetation cover or uneven ground, reducing the likelihood that coating holidays or stripped connection points would contact dry brush. Further, the study investigated the effects of through-thickness coating holidays but did not address the potential negative effects of partial coating loss from sources such as abrasion.

Summary of Covered Conductor Effectiveness

The prior sections outline field experience and laboratory studies that suggest a significant risk reduction with CC use. Although not all bare conductor failure modes are addressed by specific laboratory studies in controlled environments, sufficient high-level evidence exists to suggest that selected hazards affecting bare conductor are addressed by CC use. As shown in Table 5, there are six hazards that are largely mitigated by CC use, including animal, moisture, wind, tree/vegetation, public/ worker impact, and third-party damage. However, as discussed in the prior sections, this does not suggest that additional work is not required to address these hazards. In many cases, specific test scenarios may still add value to better understand CC use. Such tests scenarios are discussed in the Recommendations section of this report.

Table 5. Hazards that are largely addressed by use of covered conductors are shown in green.

	Hazard	Potential to Mitigate Failures		
		Bare Conductor	Covered Conductor	Sources
Primary Hazards	Tree/vegetation		Reduced risk of tree/veg contact-induced fault	Li 2010; Leskinen 2004; Ariffin 2012
	Wind		Reduced risk of phase-to-phase faulting from slapping or blowout	Leskinen 2004
	Third-party damage		Reduced risk of phase-to-phase faults from contact with kites, balloons, palm fronds, etc.	SCE 2019
	Animal		Reduced risk of animal contact-induced fault	Ariffin 2012
	Public/worker impact		Reduced risk of faults from worker contact or vehicle impact	Li 2010
Secondary Hazards	Moisture		Provides environmental protection except near hardware/dead-ends	
	Ice/snow			
	Fire			
	Extreme heat			
	Maintenance/ installation			
	UV exposure	N/A		
	Contamination	N/A		
	Lightning	N/A		

Comparison to Underground Cabling

The above-referenced literature and case studies demonstrate the advantages of CCs relative to bare conductors. The insulating polymer sheath mitigates several failure modes related to phase-to-phase and phase-to-ground faulting such as conductor slapping, animal contact, tree contact, and downed-conductor scenarios. While these benefits are critical to distribution system reliability and safety, there are additional hazards associated with overhead line constructions that cannot be reduced or eliminated by CCs. For example, CCs are exposed to ice/snow loading, contamination from salt, industrial pollutants, wildfire smoke, and conductor burndown from lightning strikes.

The third option typically considered for distribution system hardening is underground cabling. This method of construction has the potential to mitigate the same failure modes as CCs while also mitigating failure modes related to several other hazards, as shown in Table 6. By routing distribution lines underground, the conductors are protected from weather, fire, and other above-ground hazards that affect both bare and covered overhead conductors.

While there are benefits of underground distribution lines, there are also several economic and logistical challenges associated with their implementation. While economic considerations were largely out of scope for this work, a study conducted by SCE found that the cost per mile for undergrounding an existing overhead line ($3 million per mile) is roughly an order of magnitude more expensive than reconductoring with CCs ($430,000 per mile) [SCE 2019]. Underground conversions also may not be possible in all circumstances due to limitations of the terrain and local geology. For example, underground lines may not be practical or possible in mountainous areas or regions with high earthquake risk. Another consideration is the time required for implementation. Underground conversions are time-intensive projects, so a system hardening program based on undergrounding will take more time to realize any tangible benefits to system reliability/safety. Repairs to underground lines are more expensive and time-consuming due to access difficulties. Finally, there are environmental impacts from underground conversion that do not exist for reconductoring of existing infrastructure. These challenges are not reflected in Table 6 but require consideration in any mitigation implementation strategy.

Table 6. Mitigation potential of distribution line constructions.

	Hazard	Potential to Mitigate Failures		
		Bare Conductor	Covered Conductor	Underground
Primary Hazards	Tree/vegetation			
	Wind			
	Third-party damage			
	Animal			
	Public/worker impact			
Secondary Hazards	Moisture			
	Ice/snow			
	Fire			
	Extreme heat			
	Maintenance/installation			
	UV exposure	N/A		
	Contamination	N/A		
	Lightning	N/A		

Covered Conductor Risks

To understand all potential implications of implementing CCs, failure modes unique to CCs were assessed relative to available literature and testing information. The goal of this comparison was to understand the extent to which the identified CC-specific failure modes represent risks to operators that implement CCs. CC-specific failure modes fall into one of two categories: failure modes that may reduce the effectiveness of the insulating sheath, and failure modes that have a unique and independent risk profile relative to bare conductors (i.e., there is a potential for the risk to be higher than for bare conductors). Table 7 presents the potential consequence of the failure mode relative to bare conductors. The consequences for each failure mode were assigned based on whether the CC failure mode, should it occur, would be likely to decrease, increase, or have comparable risk relative to bare conductors, based on literature review and industry best practices. For example, contamination from salt may result in tracking on the surface of the insulation and may significantly reduce the insulating capacity of the sheath. In this scenario, the CC would have reduced effectiveness relative to a new CC but would still not exhibit a risk profile that is comparable or higher than that of a bare conductor. Complete failure of the CC insulation was considered in this analysis. For simplicity, localized (holiday) or partial failure was not considered. A detailed description of the rationale for each status can be found in the body of this section. Table 7 also lists literature sources and recommendations on whether additional testing is recommended for a given failure mode. As shown in Table 7, several effective mitigations were identified in literature for the CC-specific failure modes. However, there are still failure modes without known or proven mitigations that likely require further testing, research, and/or analysis.

Table 7. Risk of covered conductors relative to bare conductors and knowledge gaps.

Hazard	Scenario	Failure Mode	Consequence of Failure	Mitigation Notes	Selected Literature/ Testing	More Investigation Recommended
Fire	External fire	Potential damage to sheath, reducing effectiveness	Reduced effectiveness of CC	No mitigation effective against extreme temps	No testing or field experience found*	Yes
	Wildfire	Potential flammability of CC sheath	Reduced effectiveness of CC	No mitigation effective against extreme temps	SCE 2019	Yes
UV exposure / solar exposure	Aging / exposure of conductor covering	Embrittlement and/or cracking of conductor covering	Reduced effectiveness of CC	UV inhibitors commonly used to prolong polymer lifetime	Hendrix 2010; Ariffin 2012	No
Contamination	Moisture/ salt	Tracking insulation failure due moisture/salt (corona)	Reduced effectiveness of CC	Tracking and erosion issues are documented for 1-, 2-, and 3-layer CC under polluted conditions	Yousuf 2019: Cardoso 2011; Espino-Cortes 2014	No
	Smoke during fire	Tracking/insulation failure due to smoke/ash	Reduced effectiveness of CC	Tracking and erosion issues are documented for 1-, 2-, and 3-layer systems under polluted conditions	Yousuf 2019: Cardoso 2011; Espino-Cortes 2014	No
Animal	Animal contact	Phase-to-phase fault due to animal-damaged sheath (chewing)	Potentially higher consequence than bare	Redesign of coating to include a two-layer copper screen and use non-HDPE as the sheath material**	Ariffin 2012	No

Hazard	Scenario	Failure Mode	Consequence of Failure	Mitigation Notes	Selected Literature/ Testing	More Investigation Recommended
		Bird dropping degradation of polymer sheath	Reduced effectiveness of CC	Washing conductors may be effective to prevent degradation	No testing or field experience found*	Yes
Moisture	Moisture/salt/ oceanic exposure	Freeze/thaw cycles leading to sheath damage if CC is not co-extruded	Reduced effectiveness of CC	No mitigation identified in literature	No testing or field experience found*	Yes
		Migration of water within the sheath layer	Reduced effectiveness of CC	Proper installation hardware and procedures needed	No testing or field experience found*	Yes
Wind	Pole damage	Increased potential for pole damage (due to heavier conductor and larger wind area)	Potentially higher consequence than bare	Proper standards and procedures needed when retrofitting	Leskinen 2004	Yes
Tree damage	Tree falls, breaks conductor	Live conductor down with no outage	Reduced effectiveness of CC	Literature shows fewer ELIs as CC were introduced into system (see Taiwan section)	Li 2010	Yes
	Tree branch bridges various lines (conductors do not break)	Abrasion of sheath	Reduced effectiveness of CC	Literature shows CC reduced outages due to tree contact	Li 2010; Leskinen 2004; Ariffin 2012	Yes
		Cracking of CC sheaths	Reduced effectiveness of CC	Literature shows CC reduced outages due to tree contact	Li 2010; Leskinen 2004; Ariffin 2012	Yes

Hazard	Scenario	Failure Mode	Consequence of Failure	Mitigation Notes	Selected Literature/ Testing	More Investigation Recommended
		Heating damage to sheath following coating damage	Reduced effectiveness of CC	Literature shows CC reduced outages due to tree contact	Li 2010; Leskinen 2004; Ariffin 2012	Yes
		Corrosion of conductor due to compromised sheath	Reduced effectiveness of CC	Literature shows CC reduced outages due to tree contact	Li 2010; Leskinen 2004; Ariffin 2012	Yes
Maintenance / installation	Sheath damage due to incorrect hardware tool or incorrect stripping	Mechanical damage to sheath (dent/gouge)	Potentially higher consequence than bare	Proper standards and procedures needed	Rocha 2000	No

* Based on a thorough literature review. However, sources may exist that were not found through this effort.

** HDPE may be beneficial for other failure modes.

Risk Discussion

In total, 24 failure modes that are unique to CCs were assessed for their risk relative to bare conductors. The failure modes presented in Table 7 were identified through the joint IOU workshop. However, the frequency of these events (as well as consequence) was not within scope for this effort, and, as such, not all failure modes may present measurable risks to operators. Further, only a portion of these failure modes may result in an elevated risk profile relative to bare conductors, whereas others may only reduce the effectiveness of the covering. The following section discusses special cases from Table 7 in more detail.

Two fire-related failure modes were identified, including damage to, and flammability of, the sheath. In a “worst-case” scenario, if the sheath becomes damaged by fire or heat from a nearby fire, only the metallic conductor will remain. In this case, the effectiveness of CCs is greatly reduced, but no elevated risk relative to bare conductor would result. If, however, the sheath was only damaged in a localized area (versus extensive damage across the entire sheath), then a fault event could have the potential to concentrate heat and arcing in the area of the coating damage in a more severe manner than a bare conductor. In this case, a new, unique risk profile may exist beyond a simple reduction in CC effectiveness. In both cases, no mitigation, testing, or field experience was found in the literature reviewed. For this reason, further research, and possibly testing of these failure modes is recommended to determine the effect of sheath damage due to fire.

UV or solar exposure may accelerate the conductor sheath aging by causing embrittlement and/or cracking. Damage to the sheath may reduce the effectiveness of the CC. UV inhibitors are commonly incorporated in the conductor coating to prolong polymer lifetime [Hendrix 2010, Ariffin 2012].

Contamination from moisture/salt and smoke during fires was considered, as tracking could reduce the effectiveness of the insulation. Tracking of single-, dual-, and triple-layer CCs in heavily polluted areas and coastal areas is well documented in literature [Cardoso 2011, Yousuf

2019, Espino-Cortes 2014]. Similar to the fire hazard discussed above, if the insulation or sheath experiences significant tracking, then the CC effectiveness will be reduced.

Lightning may cause arc damage or melting of the CC that results in a down wire. Reports in the literature indicate CCs help to reduce the number of outages due to lightning, though the mechanism for failure prevention is unclear [Ariffin 2012, Leskinen 2004]. However, the presence of the CC insulation may create an increased risk during a lightning strike. For bare conductors during a lightning event, the electrical arc is more easily dissipated across the metallic surface. In the case of CCs, the insulation may concentrate the electrical arc at a single point during a lightning event, which may cause burndown [Lima 2016, Leal 2021]. Pinholes in the CC insulation may also result in a small reduction of the breakdown voltage. Although lightning arrestors help to mitigate this failure mode, additional testing or research could still be helpful in better understanding the effects of lightning strikes on CCs.

Animal chewing on the conductor coating may cause a localized area of damage such that arcing/heating may be concentrated during a fault. Therefore, this type of damage may present an elevated risk profile relative to bare conductors. Literature sources recommend use of a two-layer copper screen and non-HDPE as the sheath material to deter animals from chewing on the conductors. However, using non-HDPE coatings for the sheath material must be weighed against the benefits of using HDPE materials, especially in areas where animal chewing may not pose a significant risk. No further testing is recommended at this point, as this mitigation is well documented in literature [Ariffin 2012].

Moisture may result in sheath damage due to freeze/thaw cycles or water migration. In the case of water migration, sealing the ends of the conductor may help prevent damage. Few literature sources were found that addressed this specific failure mode or potential mitigation strategies. Additional research, analysis, or testing is recommended to address moisture ingress that could change the breakdown voltage potential of CCs.

Wind damage to poles due to the heavier weight of CCs and larger wind sway is potentially an increased risk compared to bare conductors. This risk can be mitigated by using proper standards and procedures, especially when retrofitting CCs onto existing structures. Additional analysis is recommended to understand potential pole damage due to CC weight.

Tree damage may result in multiple failure modes, as shown in Table 7. On a high level, field experience shows that the number of outages caused by tree contact is reduced when CCs are used [Leskinen 2004, Li 2010, Ariffin 2012, Rocha 2000]. CCs likely decrease the risk of tree-related failure modes. However, the literature studies reviewed do not detail the specific failure modes that are mitigated. Additional research and testing may be needed to determine the extent to which CCs reduce the risk of certain failure modes. Testing focused on long-term tree contact and mechanical testing of the polymer sheath is recommended.

Maintenance and installation considerations are different for CCs compared with bare conductors. Due to the CC sheath, care should be taken while installing CCs to minimize damage from incorrect hardware, stripping, or installation. Additionally, the span sag levels must be adjusted due to increased weight of CCs. Specialized training, standards, and procedures must be followed to account for the additional considerations for CC installation and maintenance. These standards and procedures should help minimize the CC risks and make them comparable to those of bare conductors. However, the additional training, standards, and procedures introduce the potential to increase the risk of CCs compared to bare conductors if not properly followed. No further testing is recommended at this time for this hazard, as long as proper procedures and standards are established for maintenance and installation.

Implementation and Design Considerations

In addition to new failure modes and risks that may be introduced by CCs, there also exist several special considerations for effective design and implementation of CC systems.

Hardware specific to CCs is recommended to ensure consistent and safe installation and reduce the risk of damaging the conductor insulation. This hardware may include insulation-piercing connectors (IPCs), spacers, tangent brackets, and messenger cable. If IPCs are not used, manual stripping of conductor insulation is required at hardware connection points. This creates a risk for local arcing/faults as well as the potential for conductor sheath damage and environmental ingress if not properly executed.

Replacement of bare conductors with equivalent CCs can potentially cause increased sag and can overload the poles, crossarms, or guys because they can increase both gravity and wind loads. The capacity of existing structures needs to be checked before reconductoring is considered. The span length for new lines is typically shorter than bare conductors due to the heavier weight of CCs. However, this can be overcome if a larger messenger wire with greater ultimate tensile strength is used [Cardoso 2011]. Span lengths of 40 meters are common for distribution systems but can be increased up to 400 meters with proper installation [Cardoso 2011].

Installation and maintenance procedures are necessary for CCs due to the special requirements listed above. Proper handling of CCs and considerations when retrofitting CCs onto existing infrastructure is needed. This includes but is not limited to minimizing the amount of coating stripped or removed, covering any exposed conductor, increasing line sag to account for the additional CC weight, and installing proper accessories for lighting arrestors, dead-end covers, composite poles, and crossarms [EPRI 2009 Crudele]. This requires additional personnel training to address unique aspects of CC care, special equipment requirements, and handling during installation and maintenance.

Recommendations

1. Line Tension Study

Several failure modes that affect both bare and covered conductors have the potential to be exacerbated with CCs relative to bare conductors. These are primarily related to the physical differences between the conductors such as diameter, weight, and surface characteristics, leading to potential differences in susceptibility to Aeolian vibrations, galloping, line sway, mechanical overload due to ice accretion, and others (Table 2). Therefore, a thorough understanding of these differences from an analytical perspective is recommended. Specifically, a study investigating the most appropriate line tension considering the size and weight of covered conductor is recommended, which would aid in mitigation of the identified failure modes.

2. Additional Arc Testing

The available literature was found to be promising and suggests that many of the identified failure modes are largely addressed by use of CCs. However, a few key scenarios have yet to be addressed. Further arc testing is recommended to investigate the effects of long-term contact with vegetation, ground, or other objects to better understand delayed high-impedance fault behavior. The effects of wet vs. dry conditions on arcing behavior also warrants further investigation.

3. Covered Conductor–Specific Failure Mode Testing

An understanding of CC-specific failure modes is critical to effective asset management. While implementing CCs will mitigate some risks associated with bare conductor use, there are new failure modes introduced through the use of CCs. The available literature focuses on the benefits of CCs and is relatively lacking with respect to these failure modes. Further research (and potentially testing) is recommended to better understand the following phenomena:

a. Sheath damage and flammability due to nearby fire
b. Tracking due to contamination from salt or smoke
c. Moisture ingress
d. CC sway behavior and the potential for pole damage

4. Early Fault Detection Research

Due to the insulation provided by CCs, a fallen intact conductor may be difficult to quickly detect with existing fault protection systems. Early fault detection schemes are a subject of current research, and additional investigation of this technology is recommended.

References

[Ariffin 2012] Ariffin, M. "New Aerial Cable Design Improves Reliability." T&D World. 1 July 2012, https://www.tdworld.com/overhead-distribution/article/20956196/new-aerial-cable-design-improves-reliability

[Cardoso 2011] Cardoso, et al. "Spacer Cable Pilot Shows Promise." T& D World. 1 April 2011. https://www.tdworld.com/overhead-distribution/article/20960567/spacer-cable-pilot-shows-promise

[CIGRE 1999] Cigre Study Committee 22-Working Group 11 Task Force 4, "Safe Design Tensions with Respect to Aeolian Vibration. Part 1: Single Unprotected Conductors." Electra No. 186, 1999.

[Electrical Connection 2021] "Covering the risk of bushfires" Electrical Connection. 27 Sept 2021, https://electricalconnection.com.au/covering-the-risk-of-bushfires/

[EPRI 2009] EPRI, "Transmission Line Reference Book: Wind-Induced Conductor Motion (Orange Book)." 2009.

[EPRI 2009 Crudele] EPRI, Crudele, D. "Distribution Conductor Burndown Test Results." 2009.

[EPRI 2015] EPRI, "Distribution Grid Resiliency: Overhead Lines." 2015.

[Espino-Cortes 2014] Espino-Cortes, et al. "Electric Field Analysis of Spacer Cable systems under Polluted Conditions." 2014 Electrical Insulation Conference, Philadelphia, Pennsylvania. 8 June 2014.

[Heine 2003] Heine, P., Pitkanen, J., Lehtonen, M., "Voltage Sag Characteristics of Covered Conductor Feeders." 38th International Universities Power Engineering Conference UPEC 2003, Thessaloniki, Greece, Sep. 1-3, 2003, 4p.

[Hendrix 2010] "Sunlight (UV) Resistance Gray HD-XLPE" Hendrix Aerial Cable Systems. 25 August 2010.

[Hendrix 2019] "Test Reports for HD-XLPE CV Line Aerial Cable." 2019.

[Huynh 2011] Huynh, Q. V. and B. Techaumnat. "Study on the field behavior at the contact point between a covered conductor and a dielectric solid." Conference Proceedings of ISEIM2011, 2011, 148-151.

[Kistler 2019] Kistler M. et al., "Practical Experience with High-Impedance Fault Detection in Distribution Systems." 46th Annual Western Protective Relay Conference, 2019.

[Kyushu 1997] Kyushu Electric Power Co., ‘Outage reduction and modernisation of distribution work methods.” 1997.

[Leal 2021] Leal, O.E.S. and A. De Conti. “Lightning-Induced Voltages on an Overhead Dielectric-Coated Conductor.” Electric Power Systems Research 194, 2021, 107099.

[Leskinen 2004] Leskinen, T., and Lovrencic V., “Finnish and Slovene Experience of Covered Conductor Overhead Lines.” CIGRE Session 2004 B2-207, 2004.

[Li 2010] M.-B. Li et al. “The impact of covered conductors on distribution reliability and safety.” Electrical Power and Energy Systems 32, 2010, 281–289.

[Lima 2016] Lima, et al. “Impulse withstand voltage of single-phase compact distribution line structures considering bare an XPLE-covered cables.” Electric Power Systems Research, 1-6, 2016.

[Marxsen 2015] Marxsen, T. “Powerline Bushfire Safety Program, Ignition tests – lo-sag conductor.” 2015.

[Nishimura 2001] Nishimura, F., et al. “Covered Cable Comparative Testing: HDPE & XLPE Evaluation.” 2001 IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No.01CH37294), 2001, pp. 807-812 vol.2, doi: 10.1109/TDC.2001.971342.

[Rocha 2000] Rocha, C., et al. “New Technologies, Standards and Maintenance Methods in Spacer Cable Systems.” 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.00CH37077), 2000, pp. 2410-2416 vol.4, doi: 10.1109/PESW.2000.847186.

[SCE 2019] “Application of Southern California Edison Company for Approval of Its Grid Safety and Resiliency Program (GSRP).” California Public Utilities Commission. 23 April 2019.

[Trager] Trager, B. “Spacer Cable vs. Tree Wire: Pros and Cons of two Distinct Construction Options.” Hendrix Aerial Cable Systems.

[Trager 2006] Trager, BJ. “Spacer Cable and Tree Wire Issues in Environments Containing Airborne Contaminants.” Hendrix Aerial Cable Systems.

[Wareing 2005] Wareing, JB. “Covered Conductor Systems for Distribution.” EA Technology, 2005.

[Yousuf 2019] Yousuf, et al. “Prognostic Algorithm for Degradation Prediction of Aerial Bundled Cables in Coastal Areas.” 2019 Prognostics & System Health Management Conference—Qingdao (PHM-2019 Qingdao). 2019.

Limitations

At the request of PG&E, SCE, and SDG&E, Exponent has conducted an investigation into the effectiveness of covered conductors for overhead distribution system hardening. Exponent investigated specific issues relevant to this technology, as requested by PG&E, SCE, and SDG&E. The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any reuse of this report or its findings, conclusions, or recommendations presented herein is at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings presented herein are made to a reasonable degree of engineering certainty. We have made every effort to accurately and completely investigate all areas of concern identified during our investigation. Exponent may supplement this report should new data become available.