AN ANALYSIS ON WILDFIRE MITIGATIONS EMPLOYED BY UTILITIES IN CALIFORNIA

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Employed by Utilities in California

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ABSTRACT

An Analysis on Wildfire Mitigations Employed by Utilities in California

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As climate change continues to worsen, environmental effects are felt by many people around the world. In California, some of its most damaging wildfires have been found to be started by utilities. As the state continues to suffer from worsening wildfire conditions, the utilities need to implement a variety of wildfire mitigations to help reduce the risk of wildfires that can affect the state and its residents. This paper analyzes the effectiveness of four mitigations employed across three California utilities and suggests potential ways for the mitigations to be used together. The technologies evaluated are covered conductor, rapid earth fault current limiter, distribution fault analysis, and early fault detection. Each of these mitigate different failure drivers of utility lines, whether it is due to a contact from a foreign object, an equipment failure, or another driver. Because each mitigation is more effective against different drivers, a suggestion for multiple mitigations to use together is given. This also includes a path for utilities to evaluate mitigation effectiveness in a different way that may more accurately represent how many fires are stopped by the mitigations employed.

Keywords: fire, wildfire, mitigations, wildfire mitigations, utilities, covered conductor, rapid earth fault current limiter, distribution fault analysis, early fault detection

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Chapter 1 INTRODUCTION

Over the years, people around the nation have had to deal with wildfires and their effects. As the effects of climate change worsen, so too have wildfire-related effects. Data from the National Interagency Fire Center (NIFC) show that California is one of the most wildfire prone states. Other states may have more wildfires, but California historically has the larger and more impactful fires [1]. Although some fires may be caused by natural phenomena, such as lightning, nearly 85 percent of wildfires are caused by humans [2]. Some of the largest, such as the Dixie Fire in 2021 [3], or the deadliest, such as the Camp Fire in 2018 [4], have started due to some involvement of powerlines. These fires cost both the state and the utilities that owned the power lines billions of dollars due to their size and/or casualties. In addition, there are other life-changing effects felt by the victims of these fires. Due to the increasing dangers of wildfires, the California Public Utilities Commission (CPUC) adopted new fire-safety regulations on Dec. 14, 2017 [5], which goes along with Senate Bill (SB) 901. This new regulation requires utilities to develop wildfire mitigation strategies to help prevent future fires from occurring. This paper looks at some of the mitigations that utilities in the state of California are using to help prevent wildfires and evaluates their effectiveness. It also suggests a potential combined mitigation strategy to help further boost the effectiveness of pre-existing technologies. The data from Southern California Edison (SCE), Pacific Gas and Electric (PG&E), and San Diego Gas and Electric (SDG&E) will be evaluated to suggest combined mitigation strategies.

Chapter 2 BACKGROUND

2.1: Forest Fires

Forest fires occur when ignitions start from either natural causes, such as a lightning strike, or human causes, such as parties or barbecues. Millions of acres of land are destroyed by wildfires every year from human causes, and there have not been very reliable solutions to this problem [6]. For utility caused fires, shutting off energy prior to the time when there is the highest risk for fire was one solution [6][7].

2.2: Utility-started Forest Fires

Fires started from power lines fall under those started from human causes. Figure 2.2.1 shows some of the effects of the Camp fire in 2018, the deadliest and most destructive in California history [4][8]. Since then, California utilities have been researching potential wildfire detection and prevention technologies, sometimes even taking inspiration from other countries [9].

Figure 2.2.1: Damage from the Camp Fire of 2018 [10]

2.3: Covered Conductor

One of the most commonly used fire mitigations used by California utilities is covered conductor (CC). Covered conductor, as opposed to bare conductor, is a conductor that is “covered” with insulating material to provide incidental contact protection. Covered conductor is the term used, as insulated conductor is reserved for ground overhead cable. Other parts of the world use the two terms interchangeably. Figure 2.3.1 shows an example of covered conductor. In California, as of December 2022, SCE has installed about 4,300 circuit miles of CC, PG&E has installed 960 circuit miles, and SDG&E has installed 85 miles, with efforts to ramp up over the next couple years [11][12][13]. The concept behind covered conductor is that if anything were to come into contact with the conductor, or if the conductor came in contact with the ground, there would be enough insulation that a fire would not start from any fault current before a protection device tripped/activated. While construction of CC would vary depending on the utility, the working concept remains the same. A downside of covered conductor is that it has increased weight, increasing the mechanical stress the system faces. In addition, the ends of the covered conductor are stripped back at insulator connections at pole tops. This can allow moisture to get into the insulation/sheath of the conductor and cause potential damage that may not be detected until the conductor fails [14].

Figure 2.3.1: Example of Covered Conductor from SCE [15]

2.4: Rapid Earth Fault Current Limiter

Rapid earth fault current limiter (REFCL) is a technology developed and pioneered in Australia. It is based on the principle of rapidly displacing the neutral voltage of the network in order to bring the voltage of the faulted conductor low enough to prevent a fire [9]. REFCL can be implemented using a Ground Fault Neutralizer (GFN) [11]. For successful results, the network must be pre-hardened to operate for short periods at phase-to-earth overvoltage levels up to 90%. This is because a REFCL response will raise the voltages of the other not faulted phases. The raised voltage is because of the GFN turning the faulted phase into a neutral. Figure 2.4.1 shows the result of when the faulted phase is turned into a neutral. This action can reduce failure risk and extinguish arcing without the customer noticing [16].

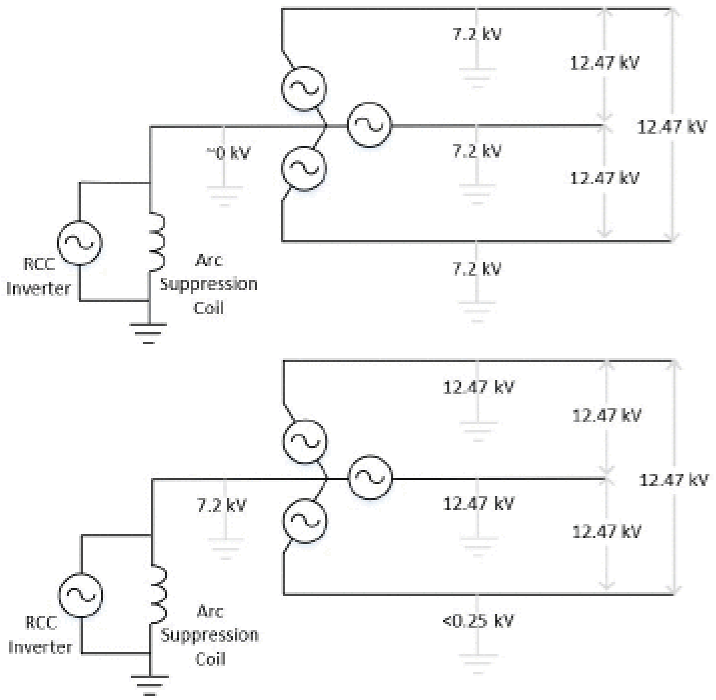


Figure 2.4.1: Normal Voltages (top) and Voltages During a Ground Fault (bottom) [17]

Any equipment that may generate standing neutral current, such as open-delta regulators, must be replaced by others that do not generate that current. Although REFCL does show some success in limiting fires [17], it has not yet been tested enough at California utilities for it to be considered a complete mitigation. In addition, REFCL is costly, the configuration has a larger footprint, and additional construction is required at a circuit's substation. Figure 2.4.1 shows an example REFCL bank that would need to be constructed at a substation.

Figure 2.4.2: REFCL Isolation Bank Used in Australia [18]

2.5: Distribution Fault Anticipation

Distribution fault anticipation (DFA) is a technology that incorporates electrical system measurements to detect the potential for pending equipment failures [12][19]. These devices monitor the circuits to assist with locating and categorizing electrical events, such as faults. The idea is that the electrical waveforms are analyzed in order to predict, or "anticipate" failures on the circuit [20][21][22]. Figure 2.5.1 shows how DFA devices incorporate current transformers (CTs) and potential transformers (PTs) to monitor the circuits. One way in which DFA may be used to mitigate ignitions is by detecting pre-fault conditions and mitigate them before they become an actual fault that may start a fire. An example is if a wind event caused a momentary fault from conductors slapping together. There would likely be minimal damage where the conductors contacted each other. However, this type of event may happen again in the future, or the minimal damage might allow for something worse to build off it. DFA lets crews know where these fault locations are, allowing them to take mitigation steps to prevent a future ignition. For a momentary event, circuit patrols may not be able to pinpoint the location if the damage isn't obvious. Although DFA can allow detection of faults, it does not have the capability on its own to prevent fires.

Figure 2.5.1: DFA System [19]

2.6: Early Fault Detection

Early fault detection (EFD) is a technology that detects high frequency radio (RF) emissions which can occur from arcing or partial discharge conditions on the system [19]. The low voltage arcs that can come from failing equipment can be detected by antennas and transmitted to engineers for evaluation [23]. Upon evaluation, the engineers can request crews to be sent out to look for and repair the failing equipment. Figure 2.6.1 shows an EFD sensor placed on the crossarm of an electrical pole. These conditions can be indicative of a failure that can cause fire if left unchecked. Examples of these conditions include severed strands on conductors, vegetation contact, or tracking of insulators. Tracking, also known as electrical treeing, is a phenomenon where the insulator material deteriorates, allowing electrical current to “track” through the insulator and the electrical pole to an electrical ground. This partial discharge can cause damage to the pole, even start a ground fire if conditions are right. Figure 2.6.2 shows an example of electrical tracking. EFD requires placement of two sensors, but the sensors are able to “bi-angulate” the location of where the arcing or partial discharge is. It can tell whether the arcing is occurring on a primary line (distribution) and the phases, or if the arcing is occurring on a secondary or service line (service to houses). Similar to DFA, EFD is only a detection system, and it requires a crew to go and inspect the location where the arcing is detected. Upon identification of the issue, repairs can be made to prevent a potential fire later. In addition, EFD may be subject to interference from cellphone signals in urban areas due to using RF as its detection method.

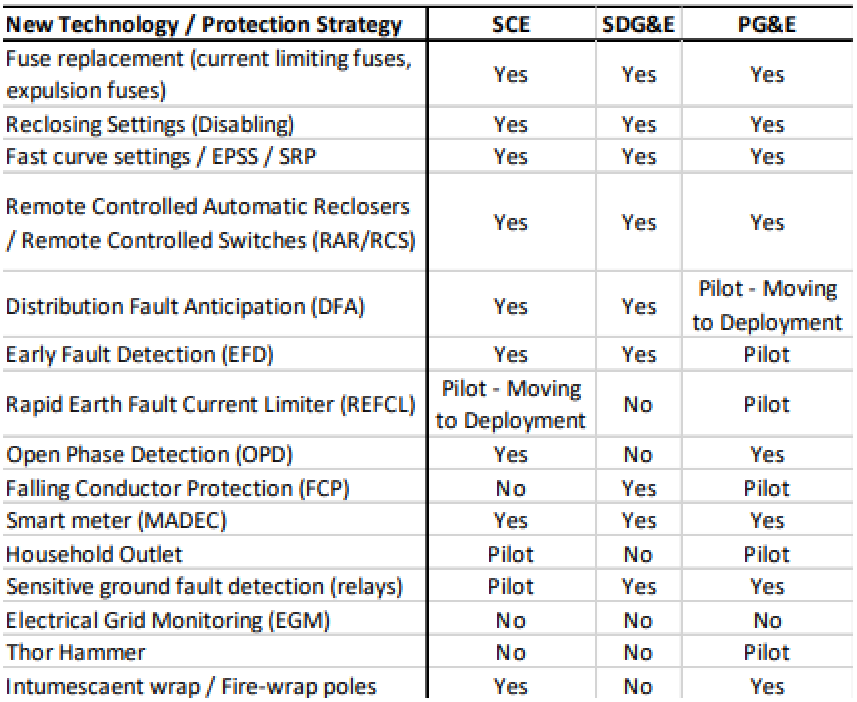
Figure 2.6.1: EFD Sensor

Figure 2.6.2: Electrical Tracking on Insulator

Chapter 3 DATA ANALYSIS

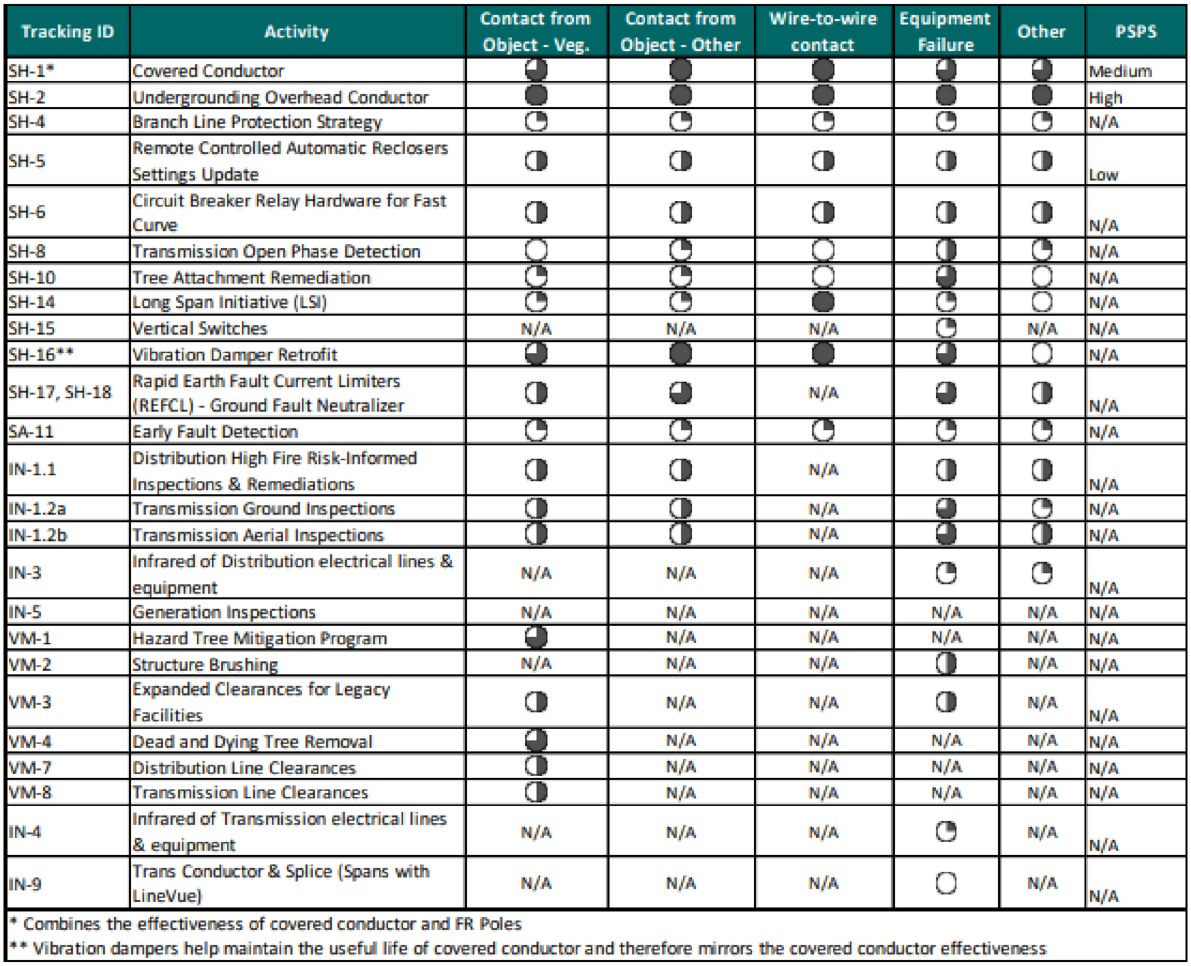
This section will perform an analysis on the available data given by the utilities in their respective wildfire mitigation plans (WMP). The data used will be based on their 2023-2025 WMP's if possible. Unfortunately, it does not seem that PG&E has any numerical data showing the effectiveness of any of the mitigations shown in section 2. An assumption they had made in risk modeling states that they had limited or no data regarding mitigation program effectiveness, and instead relied on values developed by their subject matter experts (SMEs) [12]. Analysis will still use PG&E's WMP, but there will not be any sufficient data to help support conclusions made. Table 3.1 shows an overview of technologies deployed, piloted, or not yet deployed by the three utilities. This paper will focus on CC, REFCL, DFA, and EFD. The table shows which utilities will have data regarding the mitigations. Table 3.2 is SCE's overall mitigation effectiveness using Harvey balls. Effectiveness is based on historical data, so if a mitigation may be effective against an ignition source, but there is no historical data, effectiveness would be listed as zero. However, the historical data range is not explicitly stated. Analysis, therefore, will be made using 2022 data, assuming that mitigations are more likely to be present in the most recent data. SDG&E has tables for mitigation effectiveness, but they are displayed on a per-mitigation basis.

Table 2.6.1: New Technologies/Mitigations by Utilities [11][13]



New Technology / Protection Strategy	**SCE**	**SDG&E**	**PG&E**
Fuse replacement (current limiting fuses, expulsion fuses)	Yes	Yes	Yes
Reclosing Settings (Disabling)	Yes	Yes	Yes
Fast curve settings / EPSS / SRP	Yes	Yes	Yes
Remote Controlled Automatic Reclosers / Remote Controlled Switches (RAR/RCS)	Yes	Yes	Yes
Distribution Fault Anticipation (DFA)	Yes	Yes	Pilot - Moving to Deployment
Early Fault Detection (EFD)	Yes	Yes	Pilot
Rapid Earth Fault Current Limiter (REFCL)	Pilot - Moving to Deployment	No	Pilot
Open Phase Detection (OPD)	Yes	No	Yes
Falling Conductor Protection (FCP)	No	Yes	Pilot
Smart meter (MADEC)	Yes	Yes	Yes
Household Outlet	Pilot	No	Pilot
Sensitive ground fault detection (relays)	Pilot	Yes	Yes
Electrical Grid Monitoring (EGM)	No	No	No
Thor Hammer	No	No	Pilot
Intumescaent wrap / Fire-wrap poles	Yes	No	Yes

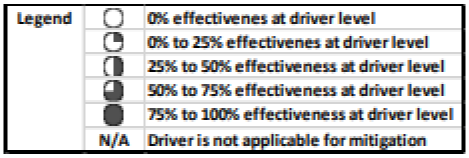
Table 2.6.2: SCE Overall Mitigation Effectiveness [11]



Tracking ID	Activity	Contact from Object - Veg.	Contact from Object - Other	Wire-to-wire contact	Equipment Failure	Other	PSPS
SH-1*	Covered Conductor	◕	●	●	◕	◕	Medium
SH-2	Undergrounding Overhead Conductor	●	●	●	●	●	High
SH-4	Branch Line Protection Strategy	◔	◔	◔	◔	◔	N/A
SH-5	Remote Controlled Automatic Reclosers Settings Update	◑	◑	◑	◑	◑	Low
SH-6	Circuit Breaker Relay Hardware for Fast Curve	◑	◑	◑	◑	◑	N/A
SH-8	Transmission Open Phase Detection	○	◔	○	◑	◔	N/A
SH-10	Tree Attachment Remediation	◔	◔	○	◕	○	N/A
SH-14	Long Span Initiative (LSI)	◔	◔	●	◔	○	N/A
SH-15	Vertical Switches	N/A	N/A	N/A	◔	N/A	N/A
SH-16**	Vibration Damper Retrofit	◕	●	●	◕	○	N/A
SH-17, SH-18	Rapid Earth Fault Current Limiters (REFCL) - Ground Fault Neutralizer	◑	◕	N/A	◕	◑	N/A
SA-11	Early Fault Detection	◔	◔	◔	◔	◔	N/A
IN-1.1	Distribution High Fire Risk-Informed Inspections & Remediations	◑	◑	N/A	◑	◑	N/A
IN-1.2a	Transmission Ground Inspections	◑	◑	N/A	◕	◔	N/A
IN-1.2b	Transmission Aerial Inspections	◑	◑	N/A	◕	◑	N/A
IN-3	Infrared of Distribution electrical lines & equipment	N/A	N/A	N/A	◔	◔	N/A
IN-5	Generation Inspections	N/A	N/A	N/A	N/A	N/A	N/A
VM-1	Hazard Tree Mitigation Program	◕	N/A	N/A	N/A	N/A	N/A
VM-2	Structure Brushing	N/A	N/A	N/A	◑	N/A	N/A
VM-3	Expanded Clearances for Legacy Facilities	◑	N/A	N/A	◑	N/A	N/A
VM-4	Dead and Dying Tree Removal	◕	N/A	N/A	N/A	N/A	N/A
VM-7	Distribution Line Clearances	◑	N/A	N/A	N/A	N/A	N/A
VM-8	Transmission Line Clearances	◑	N/A	N/A	N/A	N/A	N/A
IN-4	Infrared of Transmission electrical lines & equipment	N/A	N/A	N/A	◔	N/A	N/A
IN-9	Trans Conductor & Splice (Spans with LineVue)	N/A	N/A	N/A	○	N/A	N/A

* Combines the effectiveness of covered conductor and FR Poles

** Vibration dampers help maintain the useful life of covered conductor and therefore mirrors the covered conductor effectiveness



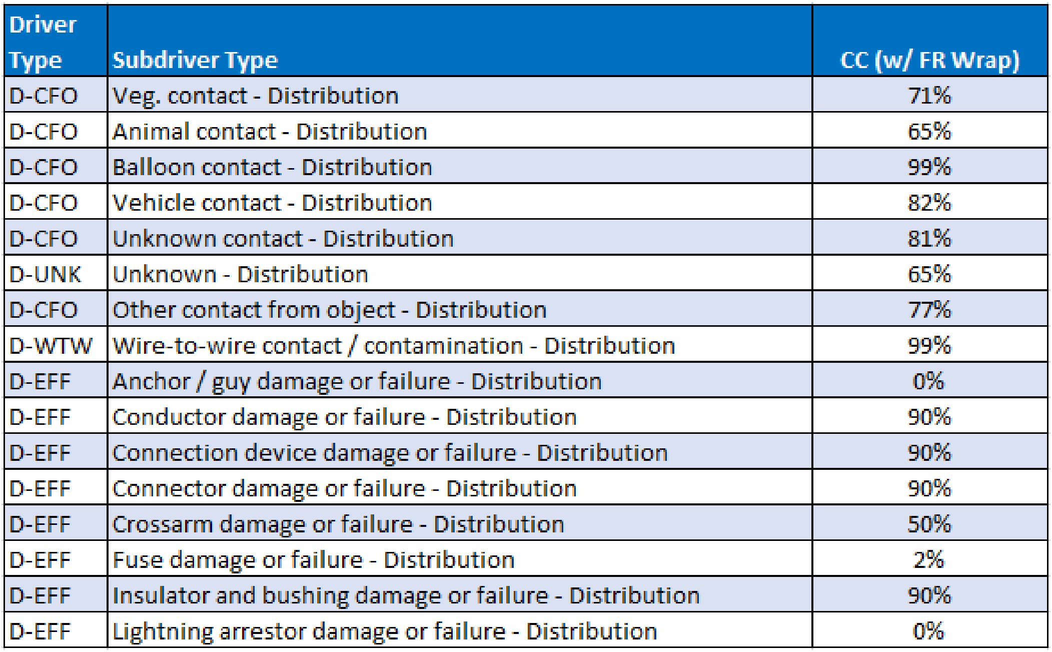
Legend	○	**0% effectivenes at driver level**
	◔	**0% to 25% effectivenes at driver level**
	◑	**25% to 50% effectiveness at driver level**
	◕	**50% to 75% effectivenes at driver level**
	●	**75% to 100% effectiveness at driver level**
	N/A	**Driver is not applicable for mitigation**

3.1: Covered Conductor

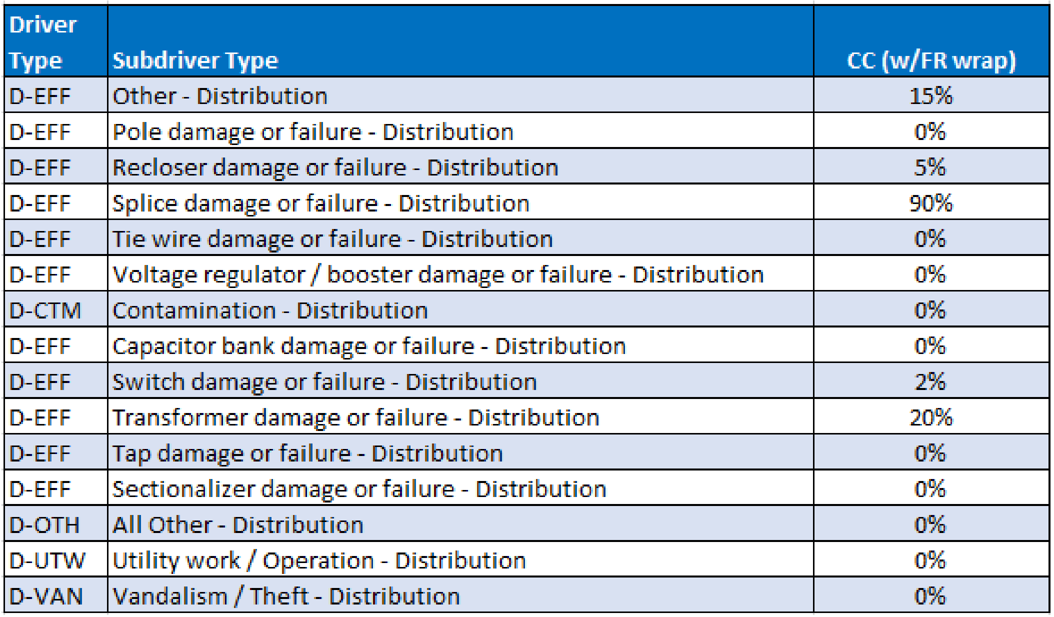
The data for the covered conductor mitigation is given in tables 3.1.1 and 3.1.2. SCE's data includes poles with fire resistant (FR) wrap at the base of the pole. Effectiveness is shown with respect to the drivers, or cause, of the ignitions. The primary drivers include contact from object (CFO), wire-to-wire contact

(WTW), equipment/facility failure (EFF), contamination (CTM), utility work (UTW), vandalism (VAN), other (OTH), and unknown (UNK) [11]. Note that CC was only used in distribution voltages. SDG&E’s data shows the mitigation effectiveness in terms of ignitions reduced per 100 circuit miles. The data is not in percentages, but rather actual ignitions that occur. PG&E has data, in table 3.1.3, showing preliminary effectiveness of CC, but the effectiveness is measured in terms of outage reduction, which includes, but is not limited to, ignitions.

Table 3.1.1: SCE CC Mitigation Effectiveness with Drivers [11]



Driver Type	Subdriver Type	CC (w/ FR Wrap)
D-CFO	Veg. contact - Distribution	71%
D-CFO	Animal contact - Distribution	65%
D-CFO	Balloon contact - Distribution	99%
D-CFO	Vehicle contact - Distribution	82%
D-CFO	Unknown contact - Distribution	81%
D-UNK	Unknown - Distribution	65%
D-CFO	Other contact from object - Distribution	77%
D-WTW	Wire-to-wire contact / contamination - Distribution	99%
D-EFF	Anchor / guy damage or failure - Distribution	0%
D-EFF	Conductor damage or failure - Distribution	90%
D-EFF	Connection device damage or failure - Distribution	90%
D-EFF	Connector damage or failure - Distribution	90%
D-EFF	Crossarm damage or failure - Distribution	50%
D-EFF	Fuse damage or failure - Distribution	2%
D-EFF	Insulator and bushing damage or failure - Distribution	90%
D-EFF	Lightning arrestor damage or failure - Distribution	0%



Driver Type	Subdriver Type	CC (w/FR wrap)
D-EFF	Other - Distribution	15%
D-EFF	Pole damage or failure - Distribution	0%
D-EFF	Recloser damage or failure - Distribution	5%
D-EFF	Splice damage or failure - Distribution	90%
D-EFF	Tie wire damage or failure - Distribution	0%
D-EFF	Voltage regulator / booster damage or failure - Distribution	0%
D-CTM	Contamination - Distribution	0%
D-EFF	Capacitor bank damage or failure - Distribution	0%
D-EFF	Switch damage or failure - Distribution	2%
D-EFF	Transformer damage or failure - Distribution	20%
D-EFF	Tap damage or failure - Distribution	0%
D-EFF	Sectionalizer damage or failure - Distribution	0%
D-OTH	All Other - Distribution	0%
D-UTW	Utility work / Operation - Distribution	0%
D-VAN	Vandalism / Theft - Distribution	0%

According to the data, CC works very well with reducing ignition risk. For each utility, CC reduced ignitions/outages by approximately 65% or higher on circuits where CC was mostly installed, in comparison to when there was no CC installed at all. From SCE’s data, CC worked best on CFO type drivers, which is its intended use case; it works especially well with regards to contacts from balloons. CC also seems to work in incidents involving conductor or connection failures. This makes sense as these events tend to involve the wire coming down, making contact with the ground or anything else in the between the conductor and the ground. Normally, when the conductor comes down, if it is energized upon contact, a ground fault is likely to occur. If the current is high enough, and there is something flammable on the ground, the chance of a fire occurring is high. With CC, there is an insulator in between the energized conductor and the ground, making it more difficult for a ground fault to occur. Similarly, CC works well in insulator/bushing failures and splice failures, which can also involve connections. In other types of equipment failures, CC does not result in a significant reduction of ignitions. This makes sense, as it is not likely for a covered conductor to stop a transformer fire if the transformer failed internally, for example.

An extra look will be taken at SCE's ignition data to see if the mitigation effectiveness provided by the utility matches their actual event data, particularly the 99% claim of effectiveness for balloon contact. Figure 3.1.1 shows a comparison of ignitions occurring in SCE's HFRA and non-HFRA territories. CC is used primarily in HFRA, so comparing ignitions in HFRA vs non-HFRA is a good estimate of CC's effectiveness. It is important to note that it is possible not all of SCE's HFRA circuits are completely covered, so the number may not be accurate, but rather just a good estimate. As seen in figure 3.1.1, the number of ignitions in non-HFRA is significantly higher than the number of ignitions in HFRA. However, CC is primarily effective with ignitions where CFO was the driver. Comparing those ignitions, HFRA had 126 while non-HFRA had 368; HFRA had approximately 66% less ignitions with CFO as the driver compared to non-HFRA.

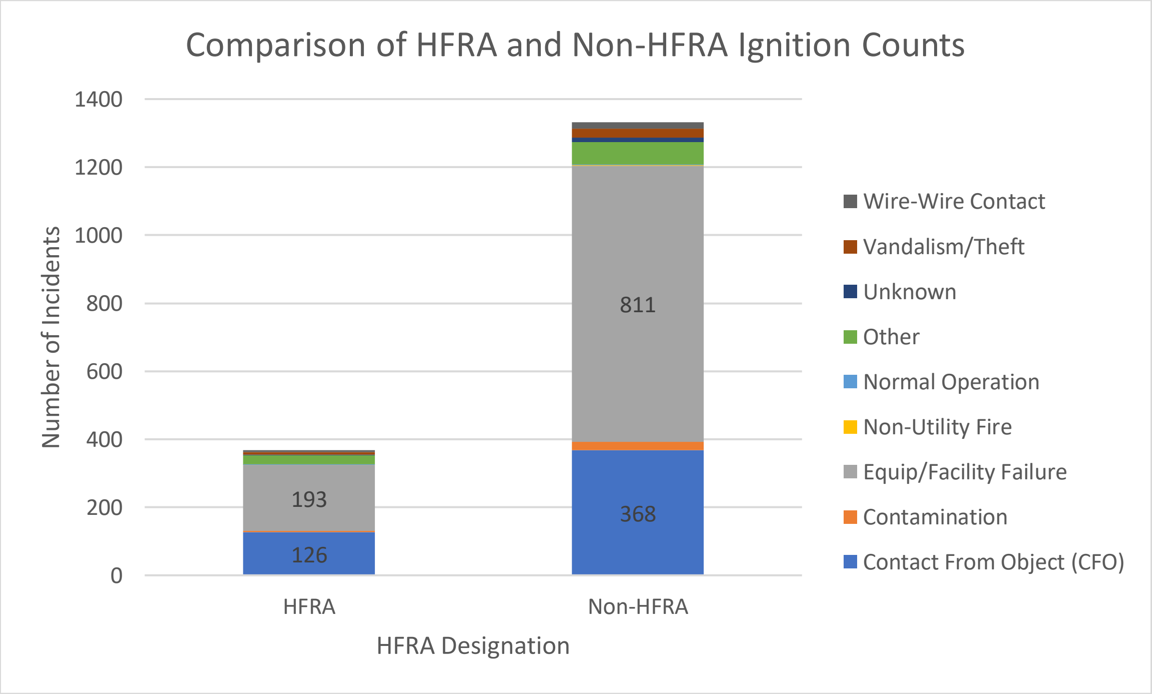


Figure 3.1.1: Comparison of HFRA and Non-HFRA Ignition Counts [24]

Looking at the CFO specifics further, figures 3.1.2 and 3.1.3 show more specifics with regards to ignitions with CFO drivers. HFRA had a total of 19 ignitions due to metallic balloon contact while non-HFRA had a total of 78 ignitions due to metallic balloon contact. This gives the effectiveness of CC to be approximately 76%, under the assumption that all of HFRA is covered. Although the actual effectiveness is less than the one given by SCE, it is still within the range of the other CFO driver specifics. This means that CC does prove to have good effectiveness against CFO events.

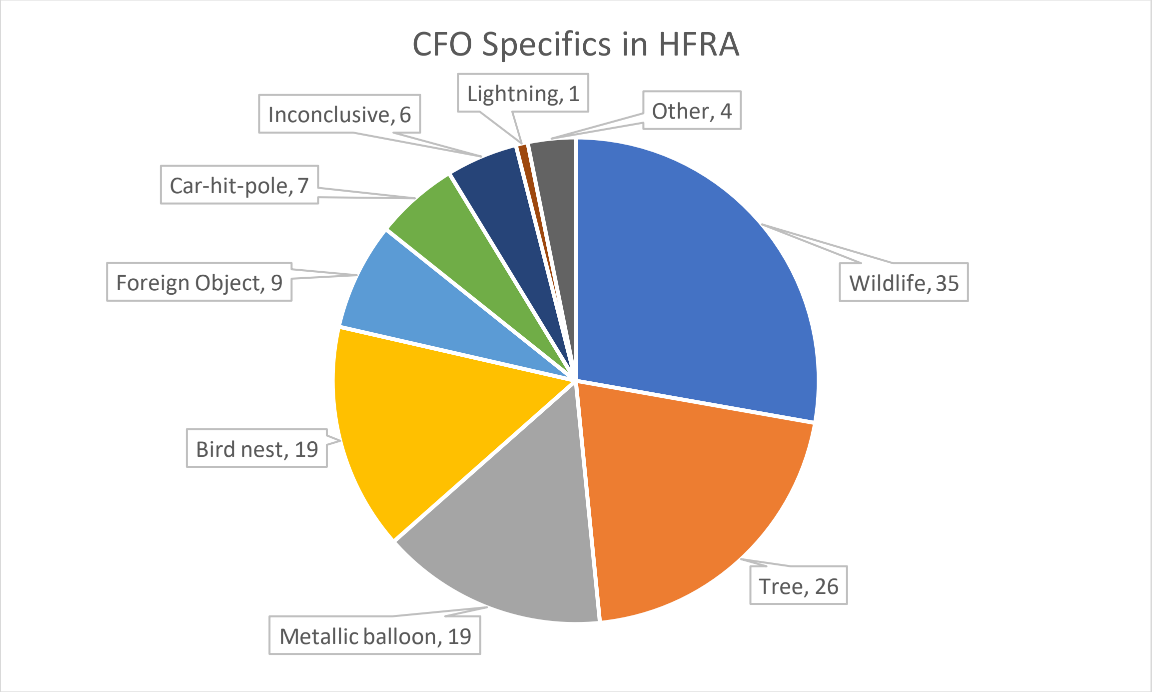


Figure 3.1.2: CFO Specifics in HFRA [24]

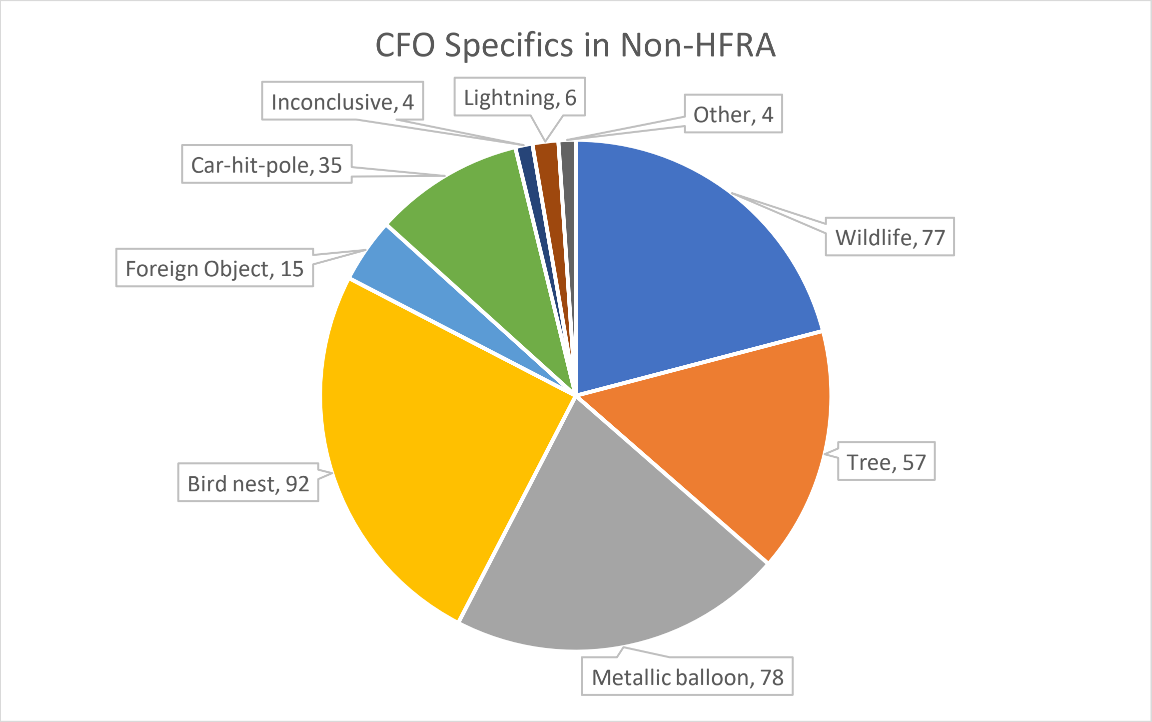
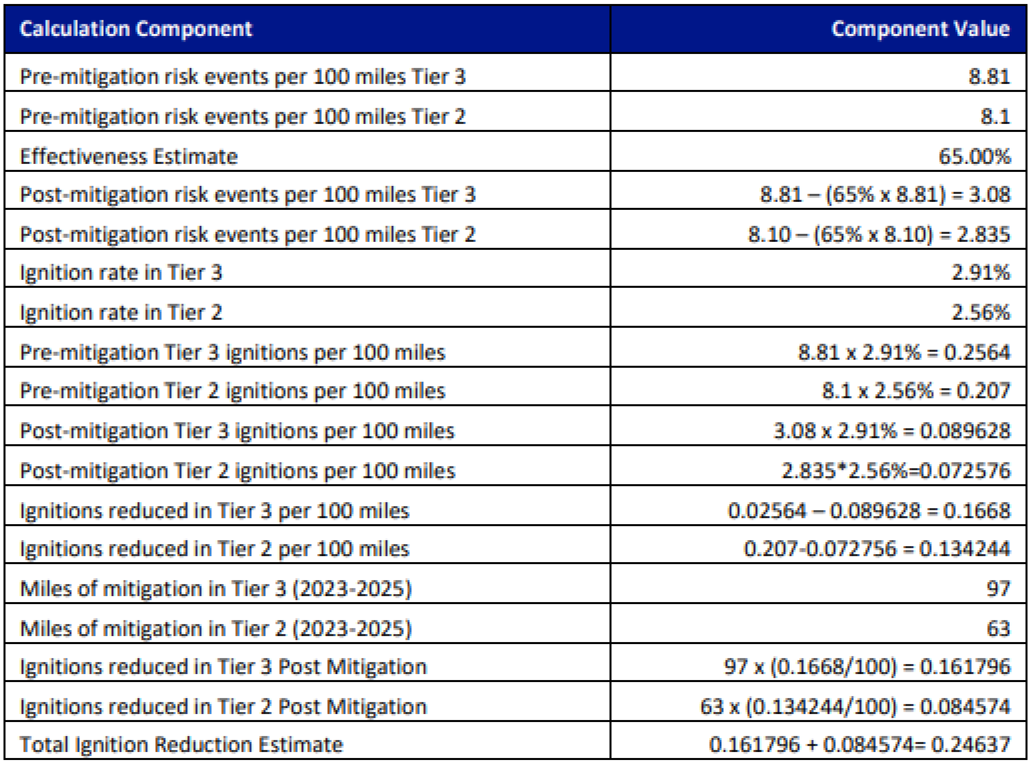


Figure 3.1.3: CFO Specifics in Non-HFRA [24]

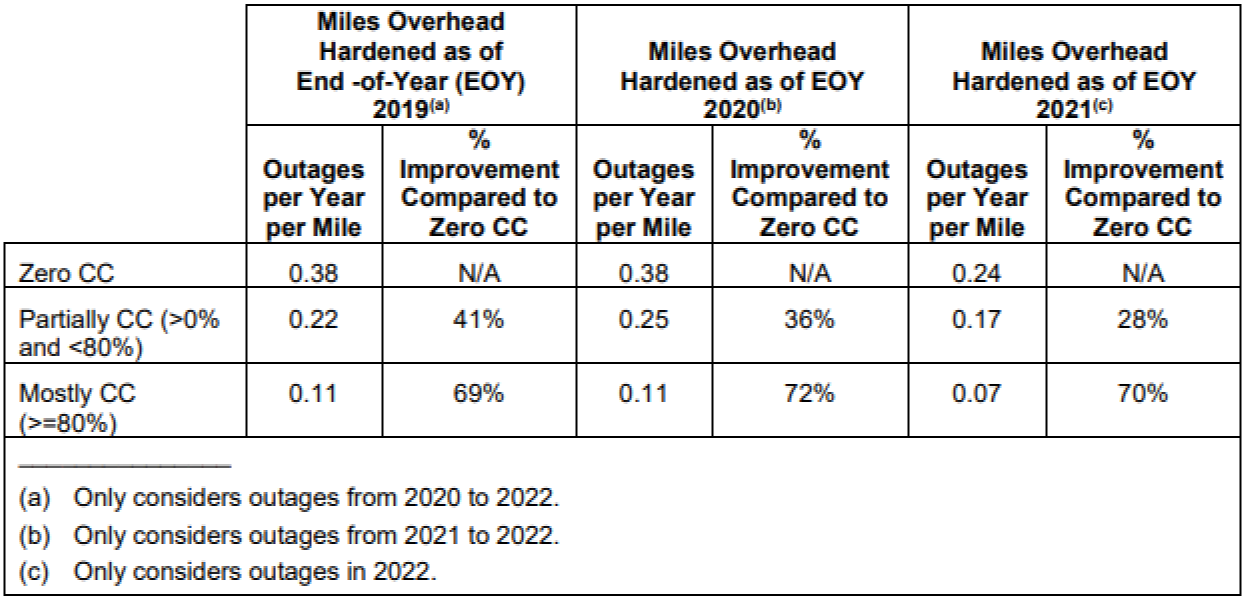
Table 3.1.2: SDG&E CC Mitigation Effectiveness [13]



Calculation Component	Component Value
Pre-mitigation risk events per 100 miles Tier 3	8.81
Pre-mitigation risk events per 100 miles Tier 2	8.1
Effectiveness Estimate	65.00%
Post-mitigation risk events per 100 miles Tier 3	8.81 – (65% x 8.81) = 3.08
Post-mitigation risk events per 100 miles Tier 2	8.10 – (65% x 8.10) = 2.835
Ignition rate in Tier 3	2.91%
Ignition rate in Tier 2	2.56%
Pre-mitigation Tier 3 ignitions per 100 miles	8.81 x 2.91% = 0.2564
Pre-mitigation Tier 2 ignitions per 100 miles	8.1 x 2.56% = 0.207
Post-mitigation Tier 3 ignitions per 100 miles	3.08 x 2.91% = 0.089628
Post-mitigation Tier 2 ignitions per 100 miles	2.835*2.56%=0.072576
Ignitions reduced in Tier 3 per 100 miles	0.02564 – 0.089628 = 0.1668
Ignitions reduced in Tier 2 per 100 miles	0.207-0.072756 = 0.134244
Miles of mitigation in Tier 3 (2023-2025)	97
Miles of mitigation in Tier 2 (2023-2025)	63
Ignitions reduced in Tier 3 Post Mitigation	97 x (0.1668/100) = 0.161796
Ignitions reduced in Tier 2 Post Mitigation	63 x (0.134244/100) = 0.084574
Total Ignition Reduction Estimate	0.161796 + 0.084574= 0.24637

Holistically, SDG&E's data shows that their system had approximately 0.2564 ignitions per 100 circuit miles in tier 3 areas and 0.207 ignitions per 100 circuit miles in tier 2 areas. Tier 2 and 3 areas high fire risk areas (HFRA) designated by the CPUC based on how likely that area is to catch fire, with tier 3 being the more likely. Figure 3.1.4 shows the most recent HFRA classifications from the CPUC. After installing CC, SDG&E had only 0.089628 ignitions per 100 circuit miles in Tier 3 and 0.072576 ignitions per 100 circuit miles in Tier 2. This resulted in a reduction of 0.1668 ignitions per 100 circuit miles in tier 3, or approximately 65%, and a reduction of 0.134244 ignitions per 100 circuit miles in tier 2, or approximately 64.9%. It's important to note that the numbers are presented like this as not every circuit mile results in a risk event, much less an ignition event.

Table 3.1.3: PG&E Preliminary Effectiveness Data [12]



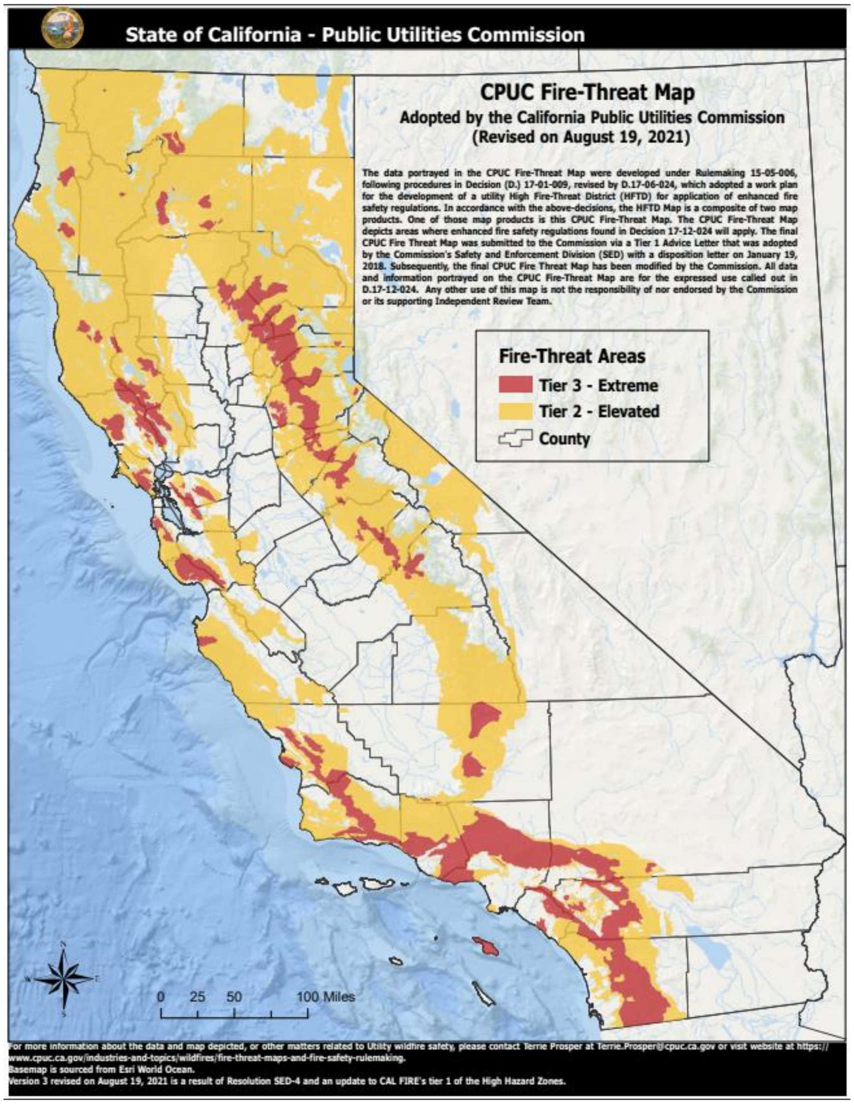
	Miles Overhead Hardened as of End -of-Year (EOY) 2019(a)		Miles Overhead Hardened as of EOY 2020(b)		Miles Overhead Hardened as of EOY 2021(c)	
	Outages per Year per Mile	% Improvement Compared to Zero CC	Outages per Year per Mile	% Improvement Compared to Zero CC	Outages per Year per Mile	% Improvement Compared to Zero CC
Zero CC	0.38	N/A	0.38	N/A	0.24	N/A
Partially CC (>0% and <80%)	0.22	41%	0.25	36%	0.17	28%
Mostly CC (>=80%)	0.11	69%	0.11	72%	0.07	70%

(a) Only considers outages from 2020 to 2022.

(b) Only considers outages from 2021 to 2022.

(c) Only considers outages in 2022.

Although PG&E's data is not as detailed, it should be noted that their data also shows that CC does reduce ignitions on circuits that are mostly CC, or covered on over 80% of the circuit. In addition, even circuits that are partially CC, or covered between 0% and 80%, show a reduction in ignitions, although to a lesser extent.



The data portrayed in the CPUC Fire-Threat Map were developed under Rulemaking 15-05-006, following procedures in Decision (D.) 17-01-009, revised by D.17-06-024, which adopted a work plan for the development of a utility High Fire-Threat District (HFTD) for application of enhanced fire safety regulations. In accordance with the above-decisions, the HFTD Map is a composite of two map products. One of those map products is this CPUC Fire-Threat Map. The CPUC Fire-Threat Map depicts areas where enhanced fire safety regulations found in Decision 17-12-024 will apply. The final CPUC Fire Threat Map was submitted to the Commission via a Tier 1 Advice Letter that was adopted by the Commission's Safety and Enforcement Division (SED) with a disposition letter on January 19, 2018. Subsequently, the final CPUC Fire Threat Map has been modified by the Commission. All data and information portrayed on the CPUC Fire-Threat Map are for the expressed use called out in D.17-12-024. Any other use of this map is not the responsibility of nor endorsed by the Commission or its supporting Independent Review Team.

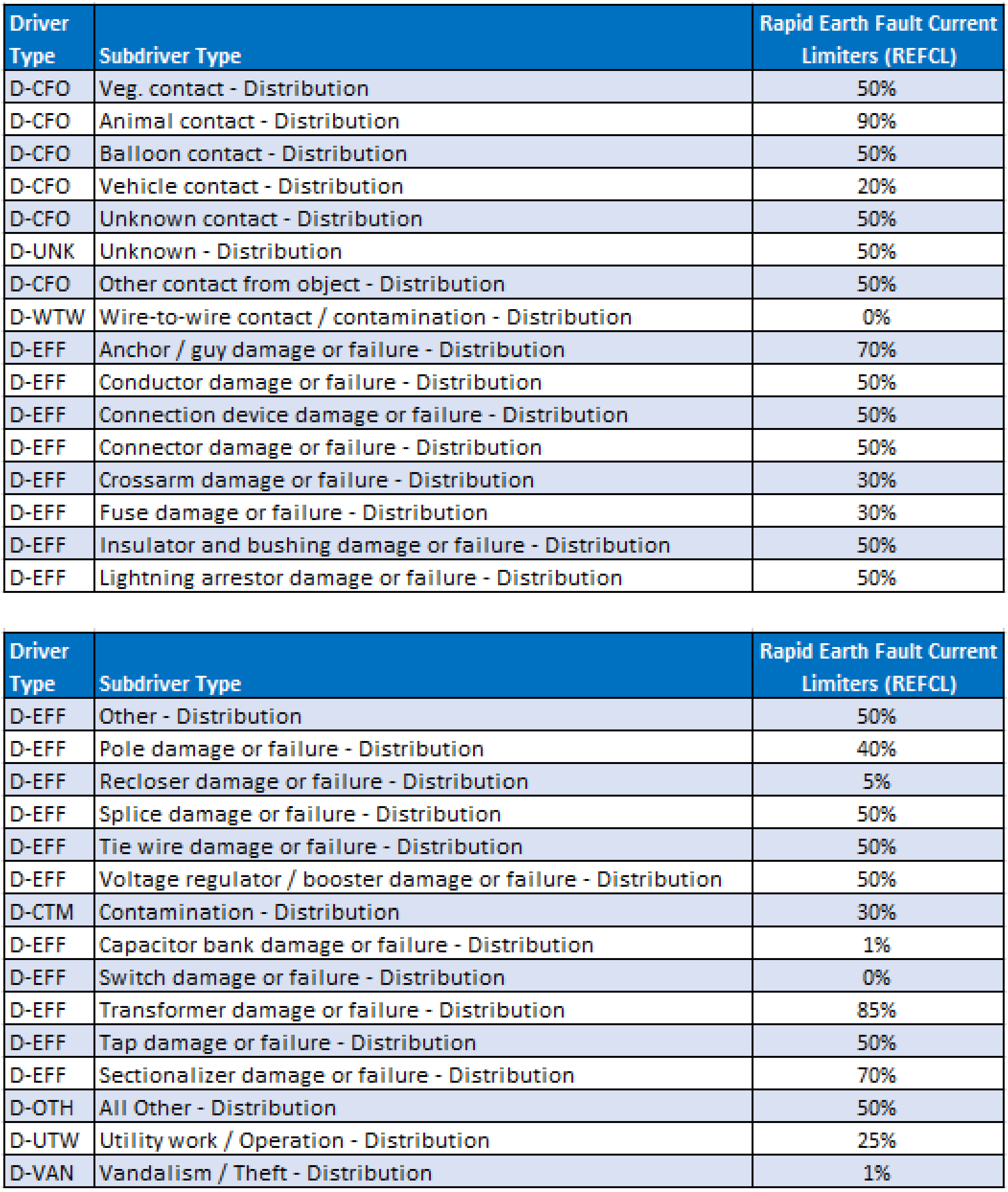
For more information about the data and map depicted, or other matters related to Utility wildfire safety, please contact Terrie Prosper at Terrie.Prosper@cpuc.ca.gov or visit website at https://www.cpuc.ca.gov/industries-and-topics/wildfires/fire-threat-maps-and-fire-safety-rulemaking.
Basemap is sourced from Esri World Ocean.
Version 3 revised on August 19, 2021 is a result of Resolution SED-4 and an update to CAL FIRE's tier 1 of the High Hazard Zones.

Figure 3.1.4: HFRA Designations from CPUC [25]

3.2: REFCL

The data for REFCL is supplied primarily by SCE. As seen in table 3.1, SDG&E does not have a REFCL pilot, while PG&E chose to pursue other, more cost effective, mitigations before continuing with their REFCL pilot [12]. The data from SCE is shown in table 3.2.1. The same incident drivers are used as with CC. In addition, the nature of REFCL does not allow it to be used in transmission voltages. Because there is a limited amount of data from the three utilities, the analysis may not be as robust.

Table 3.2.1: SCE REFCL Mitigation Effectiveness with Drivers [11]



Driver Type	Subdriver Type	Rapid Earth Fault Current Limiters (REFCL)
D-CFO	Veg. contact - Distribution	50%
D-CFO	Animal contact - Distribution	90%
D-CFO	Balloon contact - Distribution	50%
D-CFO	Vehicle contact - Distribution	20%
D-CFO	Unknown contact - Distribution	50%
D-UNK	Unknown - Distribution	50%
D-CFO	Other contact from object - Distribution	50%
D-WTW	Wire-to-wire contact / contamination - Distribution	0%
D-EFF	Anchor / guy damage or failure - Distribution	70%
D-EFF	Conductor damage or failure - Distribution	50%
D-EFF	Connection device damage or failure - Distribution	50%
D-EFF	Connector damage or failure - Distribution	50%
D-EFF	Crossarm damage or failure - Distribution	30%
D-EFF	Fuse damage or failure - Distribution	30%
D-EFF	Insulator and bushing damage or failure - Distribution	50%
D-EFF	Lightning arrestor damage or failure - Distribution	50%
D-EFF	Other - Distribution	50%
D-EFF	Pole damage or failure - Distribution	40%
D-EFF	Recloser damage or failure - Distribution	5%
D-EFF	Splice damage or failure - Distribution	50%
D-EFF	Tie wire damage or failure - Distribution	50%
D-EFF	Voltage regulator / booster damage or failure - Distribution	50%
D-CTM	Contamination - Distribution	30%
D-EFF	Capacitor bank damage or failure - Distribution	1%
D-EFF	Switch damage or failure - Distribution	0%
D-EFF	Transformer damage or failure - Distribution	85%
D-EFF	Tap damage or failure - Distribution	50%
D-EFF	Sectionalizer damage or failure - Distribution	70%
D-OTH	All Other - Distribution	50%
D-UTW	Utility work / Operation - Distribution	25%
D-VAN	Vandalism / Theft - Distribution	1%

According to the data, REFCL performs the best when the ignition drivers are due to animal contact or transformer damage/failure. For animal contact, the result makes sense, as animal contact can cause a phase-phase or phase-ground fault. Because REFCL is intended to reduce fault current as a way of mitigating fires, its effectiveness for animal contact is justified. Transformer damage/failure also somewhat makes sense because in cases where the equipment could catch fire, it seems likely that there would be some sort of fault that occurred. An example could be the oil within a transformer is bad, resulting in arcing between the ground of the tank and something energized inside the transformer. However, without more details, it is hard to be certain if this data is completely reasonable. Aside from anchor and sectionalizer failure, REFCL does not have a mitigation effectiveness above 50%. This suggests that REFCL may not be a good mitigation to use if it is the only mitigation on a circuit. In addition, the lack of sufficient data also makes it hard to evaluate how effective it actually is in California's environment, despite its effectiveness in Australia [9]. Because of the limited amount of REFCLs implemented on SCE's system, the data could be misleading, as 50% could just mean one out of two events that caused ignitions were prevented by REFCL, per the way SCE records their effectiveness (historical data).

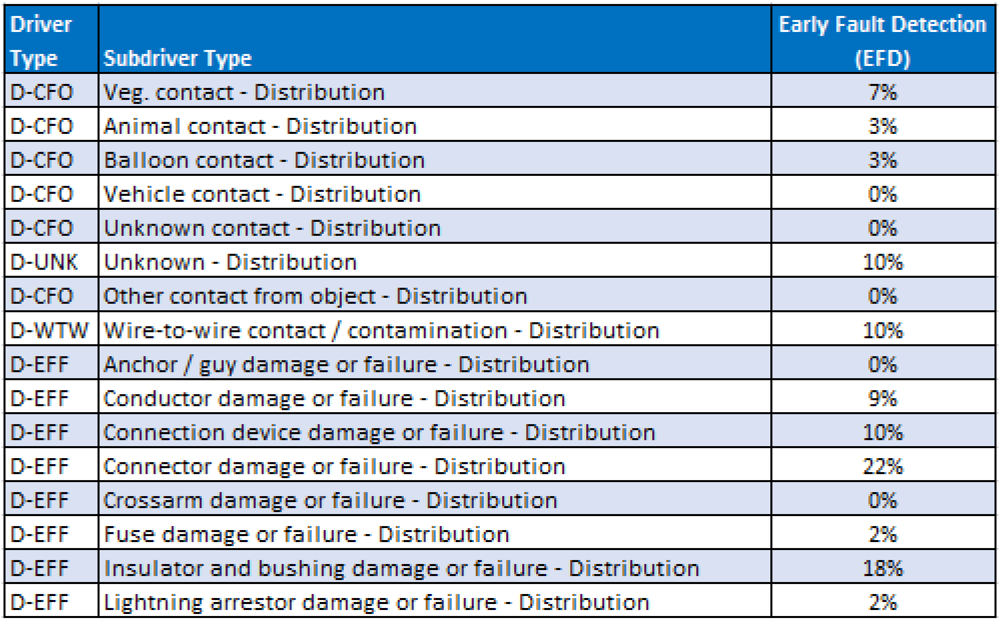
3.3: DFA

From Table 3.1, SDG&E and SCE both have DFA on their systems. PG&E has their DFA pilot moving to deployment. However, none of the companies seem to have data regarding the mitigation effectiveness of DFA. Despite the differences, SCE and SDG&E both seem to use DFA and EFD as a combination, instead of separately [11][13]. Therefore, the data will be analyzed in the following section. It is important to note that the utilities were not clear in whether the data for EFD includes DFA data or not. SCE has chosen to halt deployment of DFA for further evaluation as well, suggesting that the technology is not yet mature enough for data to be publicly published [11].

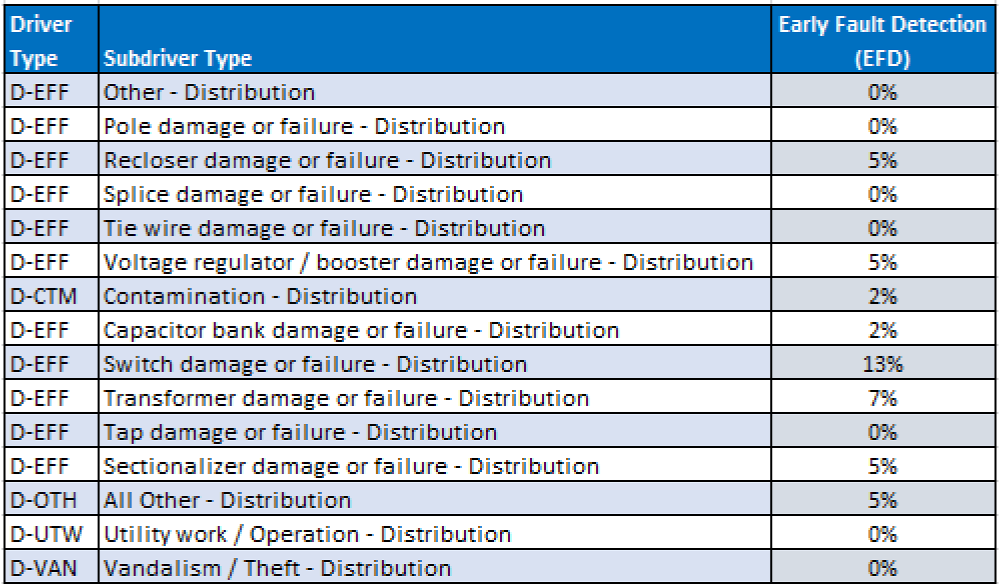
3.4: EFD

The data for EFD is given in tables 3.4.1 and 3.4.2. PG&E is still piloting this technology, so the data is not yet available for analysis. From SCE’s data, it seems that EFD is not very effective in ignition mitigation. However, EFD is not capable of preventing ignitions. Rather, it detects failures that could lead to ignitions. In addition, it requires active monitoring of the readings EFD picks up and inspection teams to go out and find the issue.

Table 3.4.1: SCE CC Mitigation Effectiveness with Drivers [11]



Driver Type	Subdriver Type	Early Fault Detection (EFD)
D-CFO	Veg. contact - Distribution	7%
D-CFO	Animal contact - Distribution	3%
D-CFO	Balloon contact - Distribution	3%
D-CFO	Vehicle contact - Distribution	0%
D-CFO	Unknown contact - Distribution	0%
D-UNK	Unknown - Distribution	10%
D-CFO	Other contact from object - Distribution	0%
D-WTW	Wire-to-wire contact / contamination - Distribution	10%
D-EFF	Anchor / guy damage or failure - Distribution	0%
D-EFF	Conductor damage or failure - Distribution	9%
D-EFF	Connection device damage or failure - Distribution	10%
D-EFF	Connector damage or failure - Distribution	22%
D-EFF	Crossarm damage or failure - Distribution	0%
D-EFF	Fuse damage or failure - Distribution	2%
D-EFF	Insulator and bushing damage or failure - Distribution	18%
D-EFF	Lightning arrestor damage or failure - Distribution	2%

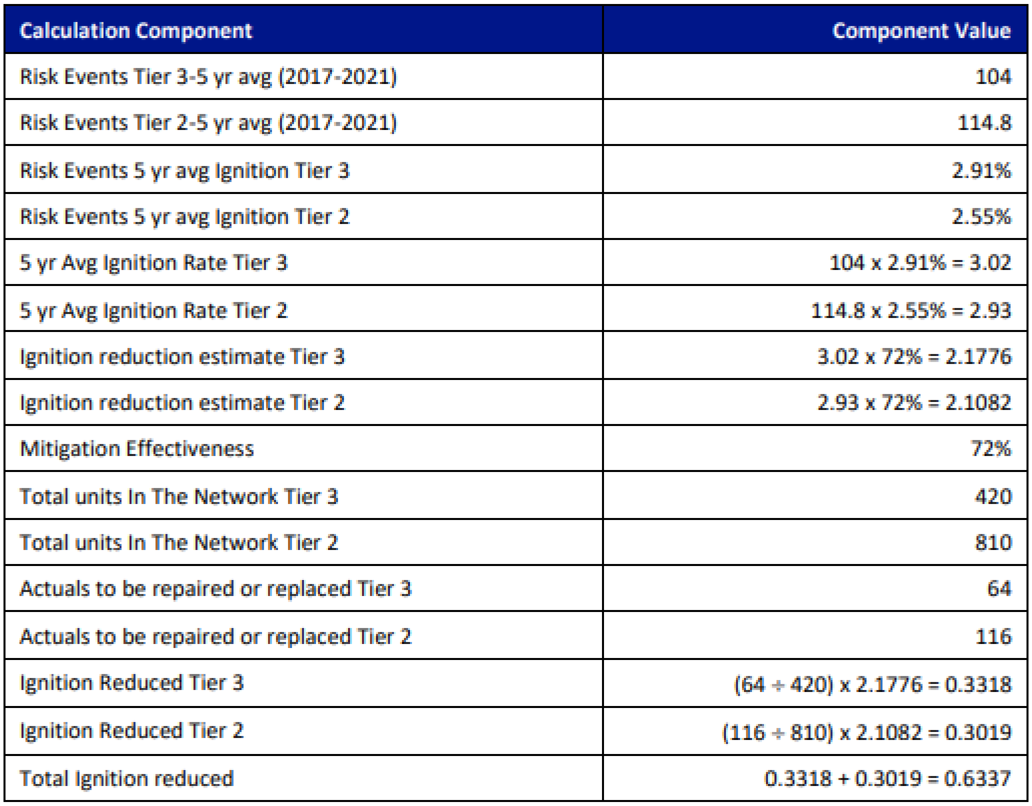


Driver Type	Subdriver Type	Early Fault Detection (EFD)
D-EFF	Other - Distribution	0%
D-EFF	Pole damage or failure - Distribution	0%
D-EFF	Recloser damage or failure - Distribution	5%
D-EFF	Splice damage or failure - Distribution	0%
D-EFF	Tie wire damage or failure - Distribution	0%
D-EFF	Voltage regulator / booster damage or failure - Distribution	5%
D-CTM	Contamination - Distribution	2%
D-EFF	Capacitor bank damage or failure - Distribution	2%
D-EFF	Switch damage or failure - Distribution	13%
D-EFF	Transformer damage or failure - Distribution	7%
D-EFF	Tap damage or failure - Distribution	0%
D-EFF	Sectionalizer damage or failure - Distribution	5%
D-OTH	All Other - Distribution	5%
D-UTW	Utility work / Operation - Distribution	0%
D-VAN	Vandalism / Theft - Distribution	0%

Using values relative to each other, SCE's data shows that EFD is most effective in mitigating ignitions due to connector damage/failure and insulator damage/failure. This makes sense, as both are the most likely to cause arcing or partial discharge, the conditions EFD uses to determine whether the equipment is failure. Figure 3.4.1 shows an example parallel groove connector. A poor connection can result in the connector having partial discharge in the connector. This poor connection can occur if it is not properly tightened. An example of an insulator failure that can cause partial discharge is tracking, as shown in figure 2.5.2.

Figure 3.4.1: Example Parallel Groove Connector [26]

Table 3.4.2: SDG&E EFD Mitigation Effectiveness [13]



Calculation Component	Component Value
Risk Events Tier 3-5 yr avg (2017-2021)	104
Risk Events Tier 2-5 yr avg (2017-2021)	114.8
Risk Events 5 yr avg Ignition Tier 3	2.91%
Risk Events 5 yr avg Ignition Tier 2	2.55%
5 yr Avg Ignition Rate Tier 3	104 x 2.91% = 3.02
5 yr Avg Ignition Rate Tier 2	114.8 x 2.55% = 2.93
Ignition reduction estimate Tier 3	3.02 x 72% = 2.1776
Ignition reduction estimate Tier 2	2.93 x 72% = 2.1082
Mitigation Effectiveness	72%
Total units In The Network Tier 3	420
Total units In The Network Tier 2	810
Actuals to be repaired or replaced Tier 3	64
Actuals to be repaired or replaced Tier 2	116
Ignition Reduced Tier 3	(64 ÷ 420) x 2.1776 = 0.3318
Ignition Reduced Tier 2	(116 ÷ 810) x 2.1082 = 0.3019
Total Ignition reduced	0.3318 + 0.3019 = 0.6337

SDG&E measured the effectiveness of EFD based on how many components on the system were detected to need repairs. They then used a 5-year average to determine the number of risk events and ignitions the circuit would have. Afterward, they used that data to extrapolate an estimated ignition reduction for both tier 2 and tier 3 areas. This results in an estimated mitigation effectiveness of 72%, assuming the trends stay consistent.

In contrast to SCE’s low effectiveness scores, SDG&E’s effectiveness score is high. This is likely due to the difference in how each utility captured the data. SCE’s captured data is in terms of drivers and how the technology mitigates ignitions from those drivers. SDG&E’s captured data is in terms of components detected and repaired/replaced. Those calculations are then used with a 5-year trend to estimate the ignitions reduced and the mitigation effectiveness. This difference makes it hard to tell what the actual effectiveness of EFD is. For example, SDG&E makes it seem like all ignitions from risk events should be considered. However, EFD would likely not catch an ignition due to animal contact, as EFD would require an inspection crew to go out. On the other hand, SCE makes it seem like EFD doesn’t work well. However, that number also includes inspection crews not going to the pre-incident site before the incident occurred, or the inspection crews not catching the failures, etc. There are more factors in SCE’s numbers than those that should be considered.

Despite the differences, the mitigation does seem to be working as intended. SCE chose to continue installation/deployment of EFD over DFA, which suggests that EFD outperforms DFA in its current state while SDG&E continue to deploy

EFD. SCE and SDG&E are in the fourth generation of the EFD technology, which hopes to increase its data collection capabilities. The additional data generated will allow for better detection of failing equipment.

Chapter 4 EVALUATION AND RECOMMENDATIONS

This section will make use of the data evaluated in the previous section and make recommendations on the mitigations used.

4.1: Covered Conductor

Based on the data, covered conductor works best in areas that would have high contact with foreign objects. This can include areas with high vegetation or areas that have a higher amount of wildlife. Even if the area is not subject to high contact with foreign objects, CC still seems to be the best general mitigation, compared to the other mitigations evaluated. Ideally, CC should replace all bare conductors in the utilities' jurisdiction. However, a replacement of all bare conductor may not be the ideal solution. All the utilities have circuits that are near the coast, where the air has more contaminants due to the seawater. Because both the sheath and the conductor now have the ability to be contaminated, there are now different points of failure compared to bare conductor [14]. Extra precautions should be taken with regards to potential contamination issues with CC. In addition, more thought must be put into whether or not CC would be a good fit for coastal circuits.

4.2: REFCL

The data is not sufficient to make a good recommendation for REFCL. More data would need to be collected in order for a reasonable recommendation to be made. However, with the data given, REFCL would work best in areas that may be more prone to equipment failures. This could be due to weather, compounded with overuse, causing transformers to overload. REFCL also works well in areas with high animal contact. The downside of REFCL is that it is expensive and has a large footprint, meaning it has limited applicability. This may explain why SDG&E have not piloted REFCL, why PG&E have not continued to deploy REFCL, and why SCE will only have it on 3 substations (circuits) by the end of 2023 [11][12][13]. Its cost and limited usage have likely put the mitigation at a lower priority for testing.

4.3: DFA

Because there is lack of data for DFA effectiveness on its own, not much can be recommended for this mitigation. However, it operates on a similar principle to EFD, except it uses circuit measurements from PTs and CTs instead of RF readings from partial discharge. It is safe to assume that wherever EFD is recommended, DFA can also be recommended as a backup, or supplemental mitigation.

4.4: EFD

Based on the data, EFD works best in areas that are prone to connector and insulator failures. In the case of connector failures, there are many ways that issues can come up. It could be due to age, corrosion, workmanship (people not properly trained), or weather (wind, rain, etc.). This means areas prone to this would be able to leverage EFD’s strengths. For insulator failures, tracking is one of the issues that tends to stem from weather, particularly rain. Again, areas prone to weather would be ideal for use of EFD. However, because it uses RF, there may be issues if EFD is used in urban areas, where cellphone signals can cause interference.

4.5: Combinations

Each of the 4 mitigations could be used by themselves, but because they are not mutually exclusive, they could be used together to potentially be more effective. CC can be used together with any of the other 3 mitigations to be more effective at preventing ignitions. For example, CC with REFCL could help increase the 90% effectiveness CC had with stopping an ignition from animal contact. Animal contact would result in a fault that REFCL could likely deal with based on the data. CC can also be combined with EFD/DFA, as CC tends to be more effective with CFO, while EFD/DFA is more effective with EFF. In both cases, there are some things to consider regarding CC. The covered nature of CC could make it difficult for faults to be detected [27]. This means that REFCL may end up not being as effective as intended. For EFD, there may be issues with the inspection process after it detects a problem. For example, if something were to happen to damage a conductor, such as corrosion, EFD would be able to detect that damage due to the partial discharge. However, if the conductor was covered, inspection crews might not be able to see where the damage is if the corrosion occurred inside the CC's sheath. Because covered conductor is stripped at the ends to allow connection to pole top insulators, moisture could get into the conductor, causing corrosion in the previous example [14]. Depending on the conditions that the circuit is in, this could very well become a common failure mode that could be found by EFD, but unable to be prevented due to inspections not finding it.

As for REFCL and EFD/DFA, they primarily prevent different issues that can cause ignitions. What they have in common is the ability to detect/prevent equipment failures. The two can be combined in areas that have a lot of equipment failures, likely due to weather. However, due to the investments needed for REFCL, both size and cost, it might be better to only have REFCL used in areas that do result in a lot of animal contact or equipment (transformer) failures. In cases where either is used with CC, it may be more cost effective to choose either REFCL or EFD/DFA. Although redundancy could be good when used together, the reactive versus proactive nature of the two technologies may better justify using one or the other. Considering the case of being used with CC, REFCL could be considered over EFD/DFA in areas with a history of animal contact and/or transformer failures. EFD/DFA should be used elsewhere to save costs.

Chapter 5 CONCLUSION

This paper evaluated several mitigations used by SCE, SDG&E, and PG&E to prevent ignitions caused by their lines. Furthermore, suggestions were made on where those mitigations should be used, and potentially tested, to collect more data on the effectiveness of the mitigations.

Through this evaluation, each mitigation performed well in some scenarios and poorly in other scenarios. CC succeeded in preventing ignitions to a high degree in events where CFO was considered the primary driver. Even in an overall view, CC had approximately a 65% reduction in ignitions caused by the utilities. It seems to be the mitigation that all utilities agreed to be effective in California. REFCL worked best in situations where faults would occur, such as animal contact or transformer failures. This is expected as this is what the technology was made to do, prevent ignitions by lowering the voltage of the faulted conductor. DFA was often combined with EFD in terms of discussion in the utilities' WMPs. However, DFA was considered not yet ready for deployment, compared to EFD. EFD had different ways of measuring the effectiveness from the two utilities that provided data. SCE measured effectiveness in terms of the drivers, making it seem like EFD was not effective at all. However, EFD requires an inspection team and cannot actually "prevent" an ignition on its own. SDG&E measured effectiveness based on how many failed or near failing equipment EFD found, assuming the rate that ignitions would occur from those failed equipment was consistent with their 5-year trend. Both utilities showed that EFD could work in preventing ignitions, but the way the data was presented had flaws in both cases.

Suggestions were also made for where the mitigations could be used most effectively, in addition to combinations of mitigations that would be good. CC was best in areas with high vegetation and areas prone to high animal contact. However, areas near the coast might want to collect more data before changing the bare conductors to covered due to the contamination risk that comes up due to coastal proximity. In addition, CC would work well with either REFCL or EFD/DFA, as CC tends to protect from CFO, while the other works with EFF. REFCL is best used with CC in areas where there is a history of animal contact or transformer failures. REFCL's large footprint prevents it from being used everywhere. With EFD/DFA, more caution is needed when implementing with CC, as EFD/DFA can detect potential issues within the sheath of the conductor, but inspection crews may not be able to determine where the issue is. Although redundancy of using REFCL and EFD/DFA could be beneficial, it may be better for the two technologies to be considered mutually exclusive.

Chapter 6 FUTURE WORKS/RECOMMENDATIONS

For future works, the utilities should start taking data on combinations of mitigations. In the WMPs, there was some mention of using REFCL with CC. The data taken from that testing should be noted as an effectiveness based on the REFCL/CC combination, and not as separate mitigation effectiveness.

REFCL should also be evaluated more for use in California. Utilities seem to be pushing it to the side for more cost-effective solutions. Although the technology is in use in Australia, and it is performing well, Australia is not California. More should be done to determine whether or not REFCL is a good mitigation to include, or if other solutions are better. Cost-effectiveness should be considered, but if a large wildfire could be prevented because of REFCL, the costs should be a secondary concern.

Another area that would need to be looked at is the issue of contamination of coastal circuits. In some cases, it may be that covered conductor actually is detrimental due to contamination from seawater. More data should be taken in whether bare or covered conductor is better, and the tradeoffs of each in those areas.

Lastly, the utilities should look at how they are capturing data for EFD effectiveness. One suggestion is to combine the ways effectiveness was measured. This means measuring the potential ignition reduction in terms of drivers. For example, if a connector were to fail, use the historical data of the connector failing resulting in an ignition, combined with how many connector failures EFD caught. This would be a better way to determine the actual effectiveness of EFD. The large difference in data values for the two utilities suggests that a different way of recording effectiveness should be considered.

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Appendix A: Acronyms and Abbreviations

CC	Covered Conductor
CFO	Contact from Object
CPUC	California Public Utilities Commission
CT	Current Transformer
CTM	Contamination
DFA	Distribution Fault Anticipation
EFD	Early Fault Detection
EFF	Equipment/Facility Failure
FR	Fire Resistant
GFN	Ground Fault Neutralizer
HFRA	High Fire Risk Area
NIFC	National Interagency Fire Center
OTH	Other
PG&E	Pacific Gas & Electric
PT	Potential Transformer
REFCL	Rapid Earth Fault Current Limiter
RF	Radio Frequency
SB	Senate Bill
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SME	Subject Mater Expert
UNK	Unknown

UTW	Utility Work
VAN	Vandalism
WMP	Wildfire Mitigation Plan
WTW	Wire to Wire Contact

Appendix B: Summary of Source [17]

A ground fault neutralizer (GFN) was developed as a tool to increase reliability and reduce electrical hazards from power systems. It has already been in use in several countries, such as Germany, New Zealand, and Brazil to reduce shock, down wire, and arc flash hazards. It is also in use in Australia for wildfire mitigation as part of the REFCL program in Victoria. SCE and PG&E are the first North American utilities to investigate the feasibility on American distribution circuits. GFN reduces voltage on the faulted phase while increasing voltage on unfaulted phases, turning the faulted phase into a neutral. This method can extinguish arcing and remove the fault without the customer noticing for temporary faults; permanent faults may still require opening of a circuit breaker for reduction of potential hazards.

The setup for the installation of the GFN required reducing the level of ground current noise. The neutral at the substation initially had 5 amperes of 60 Hz current, which was reduced to an average of 80 mA with the use of Capacitive Balancing Units.

Resistor faults were used to test the capabilities of GFN. A 20 A fuse was placed as a second line of protection but did not operate during testing. A 225-ohm and a 14400-ohm resistor were used in separate tests. The increased sensitivity of the system was able to detect the faults in the 20 tests done for each resistor. Note that the 14400-ohm resistor meant the ground current was half an ampere in the 12.47 kV system.

Some testing was also done for underground cable. The same testing was done with resistors, and the GFN proved effective.

Appendix C: Summary of Source [27]

Covered conductor was initially designed to improve the reliability of power supplies. The system makes it possible to construct electrical networks with a low failure frequency. A detailed analysis of discharge covered conductors on the ground, contact of covered conductors with tree branches, or drop of a tree branch onto the 3-phase CC system. The analysis looked at the operating and fault conditions of the CC system. It was difficult to detect partial discharge signals. However, after a period of time, the physical effects of partial discharge were able to be detected. A prototype detector was proposed for physical realization of partial discharge on covered conductor. Further descriptions were given regarding the hardware and software implementation of the prototype detector.

Appendix D: Summary of Source [22]

Failure of utility powerlines can be considered good ignition mechanisms for fires. However, many other conditions are also necessary for a fire to start. Many powerline-caused can occur without any previous warning, such as when a tree falls into an overhead conductor. Although the electrical system provided energy for the ignition to start, the tree would be considered the root cause of the ignition. Conversely, equipment may be showing signs of failing over days or even weeks before the conditions for an ignition to occur are satisfied. Existing protection and fault recording devices may be able to help in high-current events, but they may not be able to detect the low-magnitude signals from these intermittent equipment failures.

A data collection system installed in the substation, which uses existing magnetic current and potential transformers, can be used to perform waveform analytics. The data that is collected can be sent to utility stakeholders that need the information, such as operators and engineers. By studying the waveforms, the engineers can learn what is the “normal” of the system and what is the “abnormal” of the system. Through this process, engineers may be able to send out repair crews to search for, and potentially fix, any equipment that is failing before it starts an ignition.