ATTACHMENT 1

Statement of Qualifications

QUALIFICATIONS AND PREPARED TESTIMONY
OF
XIAN MING LI

Q.1 Please state your name and business address.

A.1 My name is Xian Ming (Cindy) Li. My business address is 505 Van Ness Avenue, San Francisco, CA 94102.

Q.2 By whom are you employed and in what capacity?

A.2 I am employed by the California Public Utilities Commission as a Public Utilities Regulatory Analyst in the Electricity Planning and Policy Branch of the Office of Ratepayer Advocates (ORA).

Q.3 Briefly state your educational background and experience.

A.3 I hold a Master of Science degree in Agricultural Resource Economics from the University of California Davis, and a Bachelor of Arts degree in Economics from University of California Berkeley. I joined the Electricity Pricing and Customer Programs Branch in October of 2012 and joined the Electricity Planning and Policy Branch in April 2016.

Q.4 What is the scope of your responsibility in this proceeding?

A.4 I was responsible for preparing ORA's testimony.

Q.5 Does this complete your testimony at this time?

A.5 Yes, it does.

ATTACHMENT 2

PG&E Data Request Response ORA_037-Q02

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_037-Q02		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_37-Q02		
Request Date:	June 30, 2016	Requester DR No.:	037
Date Sent:	August 4, 2016	Requesting Party:	Office of Ratepayer Advocates
PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION (CHAPTER 1)

QUESTION 2

On page 4 of Attachment A, in the Re-Review, PG&E states that the Root Cause (Probable) is: "An internal failure of one section of the lightning arrester in conjunction with external moisture resulted in full internal arc through, subsequently grounding the 'A' phase main generator output resulting in a Unit differential trip of Unit 2."

a. Please identify all information from RCE A that supports this Root Cause. In particular, please provide any information showing an internal failure of the A Phase lightning arrester.

b. If there is no information showing an internal failure of the A Phase lightning arrester, please explain why not.

c. Please explain the meaning of "external moisture" mentioned in the Root Cause.

d. Does the "external moisture" mean overspray from the hot wash?

e. If the "external moisture" does not mean overspray from the hot wash, please explain why not.

ANSWER 2

a. This information is contained in and throughout the reports provided by the independent consultants: 1) Draft Isidor Kerzenbaum Arrester Investigation, 2) Nigel McQuin Serge Arrester Investigation Report, 3) Jonathan Woodworth Surge Arrester Investigation Report. Note: These attachments are part of RCE 50607838 rev 3.

b. Not applicable. See answer to a. above.

c. External moisture can take the form of human initiated moisture, rain, fog, or dew.

d. Not necessarily. See answer to c. above

e. RCE 50607838 rev 3 went into more detail as this was a failure of the same manufacture type lightning arrester when no "hot wash" occurred. External moisture in the form of rain was the source (see answer to Question 1-d).

ATTACHMENT 3

PG&E Data Request Response ORA_037-Q06

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_037-Q06		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_037-Q06		
Request Date:	June 30, 2016	Requester DR No.:	037
Date Sent:	August 4, 2016	Requesting Party:	Office of Ratepayer Advocates
PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION (CHAPTER 1)

QUESTION 6

On pages 4-5 of Attachment A, in the Re-Review, PG&E determines that only one contributing cause identified in RCE A is still valid: "Hot washing A Phase transmission line string insulators (500kV dead-end insulators) with inadequate risk analysis contributed to a lightning arrester failure."

a. Please explain whether PG&E is stating the hot washing on July 10, 2013 was a contributing cause and why or why not.

b. Please explain whether PG&E is stating the inadequate risk analysis was a contributing cause and why or why not.

c. Please explain whether PG&E is stating both the hot washing and inadequate risk analysis were contributing causes and why or why not.

ANSWER 6

a. The activity of hot washing is considered high risk using DCPP procedures and processes. There is always is a risk that a "hot wash" could cause a flashover if not performed correctly. Since the hot wash was occurring during this RCE failure it is considered a contributor (i.e. the source of the water).

b. The purpose of the assessing risk is to ensure proper actions are taken to minimize the risk as much as possible. The hot wash was a source of water, excess water could cause a flashover. Had this activity been characterized as a higher risk additional oversite would have been implemented.

c. This question is explained in the RCE 50573100 rev 1 dated June 2015. The basis for the contributing cause is included from the excerpt below:

> Conflicting procedural guidance and less than adequate execution of AD7.DC6, On-line
>
> Maintenance Risk Management caused employees to categorize the hot wash activity as a non-trip risk, as follows:
>
> a. Legacy:

Mis-categorizing the hot wash activity as a non-trip risk led to inadequate risk perception, evaluation, mitigation, and complacency. (2007)

b. Current:

1. Conflicting guidance in AD7.DC6 can lead to classification of a maintenance activity as a trip risk or a non-trip risk.
2. There is no requirement for an independent verification when re-evaluations of risk result in a lower risk determination than previously designated (i.e., when trip risk activity becomes non-trip risk, or vice versa.)
3. There is no requirement to re-evaluate activities when risk procedures are revised. This creates vulnerability by allowing legacy issues of inadequate risk evaluations to perpetuate.

There were numerous risk evaluations performed of the hot washing activity. Risk evaluations were conducted under several revisions of risk procedures AD7.DC6, on- Line Maintenance Risk Management, and MA1.DC11, Assessment of Maintenance Risk. The DCPP risk assessment was changed over time from trip risk to non-trip risk. The non-trip risk determination was made because, it can be screened out as a ‘routine’ switchyard activity not identified as an operational risk under MA1.DC11. Additionally, under AD7.DC6, Attachment 4, it can screen out as “directly cause a reactor trip” (which differs from the definition in Section 3.15 “can significantly increase the probability of a reactor or turbine trip”). Risk determinations from PG&E Grid Control Center (GCC) reviewed by DCPP operations routinely listed the hot wash as a trip risk. The T-line wash crew understood a high risk as noted in their pre-job brief. All risk characterizations, regardless of the level of risk, resulted in the decision to proceed with the hot wash activity without adequate risk management actions.

ATTACHMENT 4

PG&E Data Request Response ORA_037-Q07

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_037-Q07		
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PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION (CHAPTER 1)

QUESTION 7

On page 29-30 of Attachment A, in RCE A, PG&E includes the following contributing causes:

- P.29: "CC1: OM1.ID4, Interface Requirements for Transmission & Distribution Facilities at DCPP in DCPP Electrical Maintenance was not fully implemented."
- P.30: "CC3: Legacy: The basis for the hot wash preventive maintenance (PM) was not properly documented per MA1.DC51, Preventive Maintenance Program. (1996)"

a. Please explain why the Re-review no longer includes these contributing causes. Why does PG&E consider them no longer applicable?

b. Please explain why PG&E's Re-review kept the following contributing cause when it has excluded the other previous contributing causes from RCE A: "Hot washing A Phase transmission line string insulators (500kV dead-end insulators) with inadequate risk analysis contributed to a lightning arrester failure."

ANSWER 7

a. Both of these items listed above were removed from the RCE 50573100 rev 1 dated June 2015 as these items were determined not be germane to the RCE.

b. There is always is a risk that a "hot wash" could cause a flashover if not performed correctly. Since the hot wash was occurring during this RCE failure it is considered a contributor, that is, the source of the water. (See answer provided to Question 6 parts a).

ATTACHMENT 5

PG&E Data Request Response ORA_037-Q08

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_037-Q08		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_037-Q08		
Request Date:	June 30, 2016	Requester DR No.:	037
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PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION (CHAPTER 1)

QUESTION 8

The Re-Review did not list the contributing causes for RCE B, are they also applicable to the A Phase flashover?

a. If PG&E does not consider the contributing causes for RCE B to be applicable to the A Phase flashover, please explain why not.

ANSWER 8

The RCE B does apply to RCE A. Both lightning arresters that failed were the same type and manufacture and occurred under similar although separate conditions, one during a "hot wash", the other during a light rain.

a. Not applicable. See above answer.

ATTACHMENT 6

PG&E Data Request Response ORA_037-Q09

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_37-Q09		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_037-Q09		
Request Date:	June 30, 2016	Requester DR No.:	037
Date Sent:	August 4, 2016	Requesting Party:	Office of Ratepayer Advocates
PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION (CHAPTER 1)

QUESTION 9

On page 33 of Attachment A, in RCE A, PG&E states that in 1996, PG&E created a preventative maintenance request for hot washes every six months to remove contaminants of its 500kV dead-end insulators and in 1998, PG&E changed the frequency to every six weeks. On page 226 of Attachment A, in RCE B, PG&E discusses a catastrophic failure in 2008 of the Unit 2 C Phase HV Bushing in which porcelain shrapnel damaged equipment and facilities. PG&E states that as a result, in June 2011 and June 2012, the lightning arresters at DCPP were switched from porcelain to polymer materials.

a. Please define the difference between HV Bushings and lightning arresters.

b. Since the catastrophic failure was an issue of the porcelain HV Bushing and not the lightning arresters, why did PG&E decide to switch the lightning arrester materials from porcelain to polymer as well? Please provide any supporting documents on this decision.

c. Since PG&E switched back to porcelain lightning arresters as a corrective action following the 2014 outage, please explain why the underlying reasons for the switch from porcelain to polymer lightning arresters are no longer a concern.

d. When PG&E made the decision to switch to polymer lightning arresters, please explain if, and provide any evidence that, PG&E considered the performance of the polymer material in the DCPP environment.

e. When PG&E switched to polymer lightening arrestors, did PG&E consider the performance of the polymer material in the context of exposure to contaminants around Unit 2?

f. When PG&E made the decision to switch to polymer lightning arresters, please explain if, and provide any evidence that, PG&E considered whether hot washes every six weeks for its 500kV dead-end insulators is appropriate given the proximity of the polymer lightning arresters.
   i. Please describe the exact distance between the Phase A 500kV insulator that

was hot washed from the Phase A lightning arrester.

ii. Did this distance change when PG&E switched the lightning arrester from polymer to porcelain? If yes, provide information on the change and the reasoning behind it. If no, explain why not.

g. Please explain if, and provide any evidence that, PG&E considered conditions of drought when determining the appropriateness of polymer lightning arresters in the DCPP environment.

h. When PG&E switched to polymer lightening arrestors, did PG&E consider the performance of the polymer material under drought conditions with exposure to contaminants around Unit 2 and hot washes every six weeks of insulators in its proximity?

ANSWER 9

a. A bushing is constructed as a device to allow current to flow from the exterior to interior of a device while maintaining insulation from ground. In this case, a transition from an overhead transmission line to the internal transformer windings. A lightning arrester provides overvoltage protection from voltage spikes/surges due to Transmission system switching or lightning striking a transmission line.

b. The nature of the catastrophic failure of the HV bushing and collateral damage caused by the failure caused DCPP to reconsider the porcelain material. Removal of the porcelain was a personal safety consideration. This is documented in the Corrective actions to RCE 50518473 U2"A" Phase CCVT Flashover Results in U2 trip document.

c. Personal safety continues to be a focus. In addition DCPP and PG&E consider Industrial Safety and Nuclear Safety in the considerations for equipment replacement. Industrial safety relates to process is to protect and promote the health and safety of employees and others who work in and about nuclear generation facilities, primarily through control of the working environment. Nuclear Safety relates to protecting the health and safety of the public. More specifically regarding lightning arresters this safety measure encompasses equipment reliability and being able to perform its function when required. The switch from the polymer type arrester to the porcelain type arrester included these considerations. Additionally in discussing the performance with the consultants DCPP retained they provided the reference to IEEE/ANSI C62.11 standard for lightning arrester certification. DCPP learned that Lightning Arresters do not fail the same as a High voltage bushing.

d. This evaluation was performed as part of the DCPP design change process. More specifically the portion of this process that was used is called the "Replacement Parts Equivalent." The evaluation associated with the replacement arrester did involve an evaluation of the performance of polymer material and included discussions with PG&E corporate specialists as well as the manufacturer.

e. Yes, DCPP specifically evaluated the Contaminants. The manufacturer specifically

stipulated to PG&E/DCPP that the polymer lightning arrester meets the IEEE and IEC standards for "Heavy Pollution". Note: Contamination is only one of the criteria used to evaluate a suitable replacement. Other considerations include, Electrical Characteristics, Mechanical Characteristics, Performance Characteristics, Physical Characteristics.

f. No. PG&E did not consider changing the frequency of hot washes on the dead end insulators when changing material for Lightning Arrester material to polymer.

    i. Distance is approximately 123 feet from the base of the lightning arrester to the base of the 500kv insulator string attached to the turbine building.

    ii. Yes, Minimally, the review determined the differences were insignificant and acceptable. The porcelain arrester was 193 inches, the polymer arrester was 182 inches.

g. Drought considerations are not a criteria as defined by IEEE Standard C57.19.100 for selecting the arrester. The vendor provided the documentation that the lightning arrester meets the IEEE & IEC criteria for "Heavy Pollution."

h. No, Lightning arresters are designed to withstand the environmental conditions as defined in the IEEE and IEC standards as stated above.

ATTACHMENT 7

PG&E Data Request Response ORA_038-Q01

Attachment 01

MPR-4057
Revision 0
June 2014

Review of Transformer Switchyard Flashover Events at Diablo Canyon Unit 2

Prepared for

Pacific Gas and Electric Company
Diablo Canyon Power Plant

MPR ASSOCIATES INC. ENGINEERS

Review of Transformer Switchyard Flashover Events at Diablo Canyon Unit 2

MPR-4057
Revision 0

June 2014

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Executive Summary

MPR was requested to review documentation and evaluate the three recent Unit 2 switchyard events to provide conclusions and initial recommendations on how to prevent future high voltage system insulator flashover events.

Based on our review, MPR reached several key conclusions. There is commonality between the three flashover events, specifically, very heavy, non-uniform contamination present on the insulator sheds and rain (or rain-like conditions) following an extended period of dry weather. The repeated sequence of morning fog followed by afternoon drying, acts to build up layers of contamination. There are distinct differences in the size, orientation, and spacing of structures surrounding the Unit 2 transformer yard versus those surrounding the Unit 1 transformer yard. These surrounding structures affect the wind and air flow patterns around the HV bushings and insulators, causing differences in the deposit rate of contaminants, with the local environment of Unit 2 being the worst. It is feasible to use computation fluid dynamics (CFD) modeling to characterize the impact of the building arrangement at Diablo Canyon site on the local wind conditions near the lightening arrestors for Units 1 and 2.

The field service conditions at DCPP are classified as "Unusual Service Conditions" by industry standards and there may not be a good correlation between environmental conditions simulated in type tests and actual field performance. Therefore, special tests performed to "qualify" suitable insulators and arresters for DCPP may be required. The in-situ insulator contamination constituents and deposition rates at DCPP are not well quantified. Understanding the constituents' composition and deposition rate will provide a basis for selecting suitable replacement equipment or determining the appropriate mitigation strategies to employ. The relative importance of the various contaminants present at DCPP (e.g., dirt, salt, and EDG combustion byproducts) is not well understood with respect to which are key drivers that lead to flashover events and in what quantities do they become key drivers. A better understanding of the contamination constituents, their distribution and deposition rates is required to properly establish the in-service functional requirements for the equipment. Installation of additional monitoring equipment could help detect trends in the buildup of contaminates before they cause flashovers. There are a number of design changes that could be implemented to improve the robustness of the equipment or mitigate the buildup of contaminants.

MPR developed several recommendations to determine the appropriate corrective action, or combination of actions, that will be successful in precluding future flashovers. Specifically, DCPP should: minimize the generation of airborne dust and dirt onsite, characterize the insulator contamination constituents and deposition rates by periodically sampling the contamination accumulating on the Unit 2 LAs, conduct a series of contaminated insulator breakdown tests to determine the relative importance of the various constituents, develop a CFD model to characterize the impact of the building arrangement on the local wind conditions near the lightening arrestors for Units 1 and 2, establish the in-service functional performance requirements for the transformer yard bushings and insulators and compare these requirements with the type testing performed by various vendors in accordance with industry standards,

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evaluate the feasibility of returning to porcelain insulator surge arresters, and prepare an evaluation of alternatives of mitigating actions that could be implemented to prevent future flashover events.

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1 Introduction

1.1 PURPOSE

The purpose of this report is to provide the results of MPR's investigations, conclusions, and recommendations concerning the resolution of flashover events in the Unit 2 Main Bank Transformer switchyard at Diablo Canyon Power Plant (DCPP).

1.2 BACKGROUND

In the normal electrical generating alignment, power produced at each Diablo Canyon Power Plant (DCPP) unit is transmitted offsite via a main bank transformer (MBT) that feeds the 500 kV transmission system. Each unit has three MBT transformers (one for each phase) along with a surge arrester connected to the 500 kV line between the transformer high voltage bushing and the first transmission line tower out from the MBT transformer yard. The surge arresters are designed to protect the high voltage winding of its associated MBT against impulse and switching surges originating on the transmission line.

Regarding the outdoor high voltage (HV) insulating systems, the necessary minimum creepage distance of the HV insulators is established by determining the extent of dirt and pollutants (called contamination) which accumulates on the insulators. DCPP is located in a "Heavy Contamination" condition area per industry standards, and extensive accumulation of contamination on the insulators is common. The high voltage bushings and insulators in the DCPP MBT switchyards (except for the overhead insulators) are silicone polymer, which is intended to help minimize insulator contamination due to its normal hydrophobic surface that retards the buildup of a conducting film. The overhead dead-end insulators are ceramic and they have twice the rated creep distance required.

Three recent flashover events occurred in Unit 2:

On October 11, 2012, DCPP Unit 2 automatically scrammed from 100 percent reactor power following a flashover to ground of a 500 kV capacitive coupled voltage transformer (CCVT) bushing. The failed CCVT bushing insulator was made of silcone rubber polymer material. It was installed in 2009 as a replacement for the ceramic CCVT bushing insulators that were part of the original plant design. The cause of the failure was due to contamination accumulation on the insulators. A contributing cause was insulator minimum creepage distance was not consistent with industry codes and standards for the contaminant levels present at DCPP. See Licensee Event Report 50-323/2012-002-01 (Reference 1).

The CCVTs were subsequently removed from the main transformer yard and metering associated with them relocated to the 500 kV switchyard CCVTs (Reference 1).

On July 10, 2013, the DCPP Unit 2 Phase A lightning (surge) arrester in the MBT yard flashed over to ground during a periodic hot-washing of the 500kV transmission line string insulators (dead-end insulators). The flashover resulted in a differential relay actuation, automatic trip of the main turbine and main generator output breakers, and a reactor scram. At the time of the July 10, 2013 event, DCPP Unit 2 was operating at 100 percent power.

The failed lightning arrester insulator was made of silcone rubber polymer material. It was installed in 2009 as a replacement for the ceramic insulators that were part of the original plant design.

The periodic hot washing of DCPP overhead horizontally-oriented dead-end insulators has been going on for many years, arising from the failure of 500 kV dead-end insulators at the PG&E Round Mountain switchyard in 1996. The hot washing practice has been changed since this flashover occurrence. See Licensee Event Report 50-323/2013-005-01 (Reference 2).

On February 2, 2014, during a rainstorm, DCPP Unit 2 experienced an automatic scram from 100 percent reactor power as a result of a failure of the lightning arrester on the Phase B 500 kV MBT.

The failed lightning arrester insulator was made of silcone rubber polymer. A contributing factor for the February 2014 failure was contamination accumulation on the insulators due to heavy contamination of the lightning arrester's insulator sheds. See Licensee Event Report 50-323/2014-001-00 (Reference 3).

Several important points regarding this in-service operating experience are germane:

1. Over the same timeframe, no flashovers have occurred in the Unit 1 MBT switchyard, which has similar equipment, electrical design, and functional arrangement.

2. There is a difference in the layout of surrounding buildings that are adjacent to the Unit 1 MBT switchyard compared to the Unit 2 MBT switchyard, which influences the prevailing winds experienced within the switchyards.

3. The original plant equipment had porcelain HV insulators, which provided many years of reliable service until there was an explosive failure in August 2008 (Unit 2 MBT C HV bushing). In 2009, the Unit 2 MBT switchyard HV insulators (CCVTs, MBTs, and lightning arresters) were changed to polymer because of a personnel safety concern due to the extent of the debris field of broken porcelain shards.

1.3 DESCRIPTION OF WORK PERFORMED

MPR reviewed the expert evaluations, root cause analyses, extent of condition evaluations conclusions and recommendations for the three DCPP switchyard events identified above. This included reviewing the materials used to construct the affected insulators and arresters, as well as evaluating alternative materials and coatings. The documentation reviewed is summarized in Appendix B.

MPR developed a plan to quantify the site-specific environmental conditions and the required performance conditions. This plan involves future modeling, collecting in-situ sampling of contaminant constituents, and measuring buildup rates at DCPP. Once quantified, the environmental conditions can then be used by DCPP at a later date to determine whether the type-testing that the lightning arrester vendor (ABB) has already performed adequately bounds the DCPP-specific performance requirements.

MPR also provides in this report initial recommendations on how to best proceed forward to preclude future high voltage system insulator flashover occurrences.

2 High Voltage Insulator Issues

2.1 Porcelain or Ceramic Insulators

Porcelain and ceramic are inert, stable materials which can withstand heat and arcing without serious surface degradation. While these types of insulators have a long in-service track record, they do have some drawbacks such as heavy weight, fragile properties which impose careful handling, and failure that encompasses shattering into sharp pieces (Reference 4). In the case of DCPP in-service experience, the prior porcelain HV insulators provided many years of reliable service, although some periodic maintenance (washing, greasing) was required. However, in 2008, one MBT HV bushing failed.

MPR has been unable to locate domestic sources of porcelain CCVT bushings, MBT bushings, or Lightning Arresters (LAs). There is a possibility that such devices could be obtained from Japanese suppliers.

2.2 Polymer or Silicon Rubber Insulators

Polymer insulator technology began in the 1940s and came into general use on transmission lines in the 1980s. Polymer materials for arrester housings were also first introduced in the 1980s (Reference 11). Polymeric insulators offer advantages over porcelain and ceramic insulators, especially for HV applications. These include lighter weight (20% in comparison), significantly reduced size, easier handling, less vulnerable to mishandling damage, lower power loss, greater vandalism resistance (e.g., gunshot damage), no sharp or dense projectiles emitted upon failure, greater seismic resistance, and better performance while subjected to contamination on their insulating surfaces (References 4, 5, and 6).

A major advantage that polymer insulators exhibit is greater resistance to the flow of water on its surface, described as hydrophobicity. Water on a hydrophobic surface will quickly form individual droplets and not flow in large-area thin films across the surface. Hydrophobic insulator surfaces can support larger electric fields without arcing. However, heavily polluted polymer insulators can transition from having hydrophobic surfaces to hydrophilic (easily wetted) if the pollution layers grow too thick. This phenomenon is shown in Figure 2-1 (from Reference 15).

Specifically, for silicone rubber insulators, the surface exudes molecules that can actually engulf surface contaminants and thereby retain hydrophobic properties even when polluted. However, this property can be overwhelmed in the presence of heavy contamination. But due to the dynamic nature of the silicone rubber surface, the insulator surface will recover its hydrophobic properties immediately when the contamination is removed. Therefore, polymer insulators are preferred in contaminated outdoor environments (References 7 and 8).

High strength electric fields have a damaging influence on a polymer material when it reaches a value sufficient to bring about surface discharges. The discharges over the surface (for example in wet conditions) will quickly spoil the hydrophobicity (Reference 8). In the worst case (as in a complete loss of hydrophobicity), the polymer insulator will behave like conventional ceramic insulators (Reference 7) as is illustrated in the bottom of Figure 2-1. Also, in the event that a polymer insulator is overstressed and the device fails, the polymer splits open and releases energy without splintering into projectiles or sharp shards as porcelain insulators can, which improves personnel safety (Reference 9).

Accordingly, relative to ceramic insulators, polymer insulators are considered the best material in high contamination environments according to both predominant manufacturers (Reference 10).

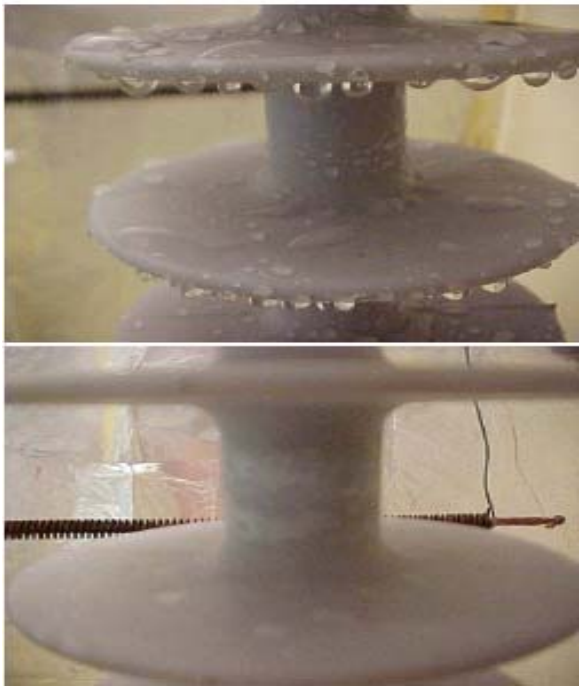

Figure 2-1. Silicone Rubber Insulator Undergoing Salt Fog Aging Test Showing Loss of Hydrophobicity (top is after 2 years of testing, bottom is after 4 years)

2.3 ENVIRONMENTALLY CONTAMINATED INSULATORS CAN FLASHOVER

When high voltage insulators are in-service outdoors, atmospheric dust, dirt, and oceanic salt can build up on the insulator surfaces. Several investigators have proven that the flashover mechanism of silicone rubber insulators [which typically have hydrophobicity] is significantly different from that of a porcelain or glass insulator (Reference 12). Highly contaminated or polluted silicone rubber insulators can experience a flashover, when wetted, due to the following general progression:

Step 1 Pollutants are deposited over time on the insulation surfaces, sometimes accumulating into relatively substantial films.

Step 2 As the dirty insulator surface is moistened due to atmospheric humidity such as fog, dew, or light rain, the pollution layer becomes conductive. The aqueous layer decreases the surface resistance resulting in the flow of leakage currents through the surface film.

Step 3 The leakage tends to increase the film temperature, most rapidly where the current density is greatest. Eventually evaporation of the moisture in these areas causes drying (dry banding) and local areas of high resistance relative to the wet areas. This results in greater voltage drop across the dry areas, and overall non-uniform voltage distribution.

Step 4 Spark discharges then occur across the high resistance areas (dry band arcing), with the spark current limited by the resistance of the wet low resistance regions of the insulator.

Step 5 If the pollution conditions persist, the spark discharges increase in intensity until ultimately the current is no longer limited by the wet portions of the insulator and complete flashover occurs (Reference 4).

2.4 ENGINEERED FLASHOVER OF MODERN SURGE ARRESTERS

A modern polymer-insulated HV surge arrester, such as those installed in DCPP Unit 1 and 2, are engineered to flashover in a prescribed manner when overloaded and performing their function. Specifically, the overloaded HV surge arrester will sacrifice itself by failing short circuit and shunting the damaging surge to ground, thereby protecting nearby high-value equipment.

The design life of a modern (ZnO technology) arrester can reasonably be expected to be at least as long as the equipment it is protecting – nominally accepted to be 30+ years (Reference 14). The extreme nonlinearity of the metal oxide is such that they normally conduct only a very small current, but quickly transition to conducting very large currents during overloads. The hollow tubular internal construction of this device contains an enclosed gas volume which might explode due to the pressure increase caused by the heat generated from short circuit arcing.

Accordingly, these arresters are fitted with a *pressure relief system* that will act quickly to release the enclosed gas volume to the outside atmosphere, at the top and the bottom of each unit. This results in two ionized gas streams being ejected outside of the arrester during an overload event. When the two gas streams meet, the internal arcing will commute to the outside and allow the energy to bypass the arrester and avoid a catastrophic shattering of the device (see Figure 2-2).

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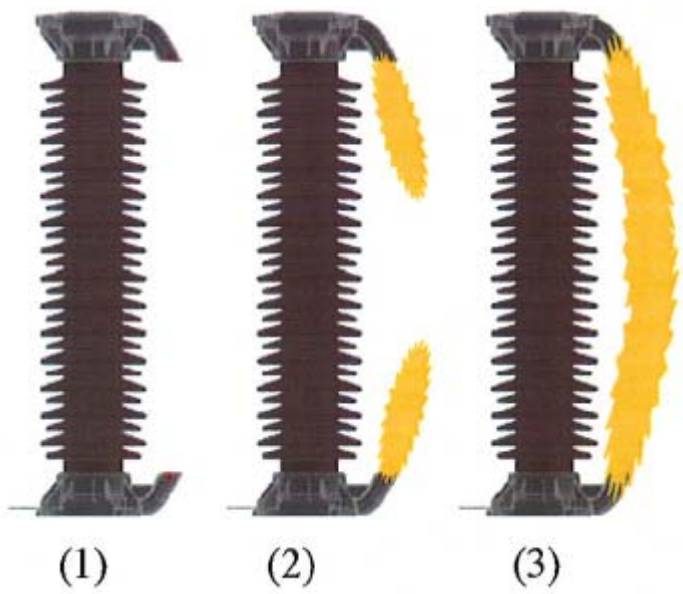

(1) Normal condition,

(2) Arrester has failed short-circuit, pressure relief plates open and gas begins to be expelled, and

(3) The two gas streams meet and the internal arc is commuted safely to the outside. Industry terminology often refers to "pressure relief operation" of this type of surge arrester (Reference 14).

Figure 2-2. Operating Principle of Pressure Relief Device of ABB Type PEXLIM silicone-housed tube Surge Arrester

Internal Flashovers Versus External Flashovers - Figure 2-2 illustrates the typical sequence for a modern silicone rubber insulated metal oxide surge arrester flashover, which is triggered by internal arcing (arising from an overload event). The initial internal arcing is usually commutated to an external flashover, as described in the sequence above. However, occasionally a surge arrester encounters a flashover that commences externally. Because of the arrester's inherent voltage clamping characteristic, it is nearly impossible for an arrester to commence a flashover externally without external assistance. Causes of such external assistance include severe [shed] contamination in conjunction with fog or high humidity (Reference 14).

3 Constituent Causes of DCPP Flashovers

The following five issues are constituent causes of the DCPP Unit 2 flashover events.

3.1 DIRT

3.1.1 Insight from Professional/Academia Publications

Airborne dirt, dust, and other industrial airborne contamination can cause aging and degradation of the [insulator] polymers (Reference 15). This is recognized to the extent that the Koeberg Insulator Pollution Test Station located on the coast of South Africa (characterized by dry summers, high winds, mist banks, and heavy marine and industrial pollution similar to DCPP) includes in its test monitoring regimen a quantitative insulator deposition measurement of dust/dirt called the Directional Dust Deposit Gauge (DDDG) in assessing HV insulation performance (Reference 16).

Also, wind tunnel testing at a PG&E field exposure test facility (Moss Landing, California) included utilizing kaolin clay along with salt for contaminating insulators (Reference 17). The PG&E investigators produced insulator contamination levels and distributions in a few hours that resemble natural contamination accumulated on outdoor insulators for several months. Atmospheric dust was found to contain soluble salts, fertilizer, and industrial chemicals. The PG&E investigators made calculations of the dielectrophoretic forces due to the electric field surrounding the insulator acting on the dirt particles to cause preferential deposition.

3.1.2 Insight from PG&E Documentation or Legacy Experience

DCPP documented several episodes of Unit 2 switchyard excessive dust/dirt adversely impacting switchyard components. Specifically, on June 13, 2012, the Unit 2 MBT 2B exhibited a high oil temperature alarm, determined to be due to the radiators being fouled with dust and dirt. This was similar to a high temperature event on the same transformer in 2007 (Reference 18). Two additional high oil temperature alarms were noticed on January 22, 2013 on the Unit 2 A and B MBTs, with investigation finding that the radiators were fouled with dust and dirt. Once the MBTs were cleaned, for all three events, oil temperatures returned to normal (Reference 19).

These recurring radiator fouling episodes indicate that airborne dust and dirt are contributing to high contamination levels in the Unit 2 MBT transformer area. The impact of these events are similar to that of salt deposits on surge arresters resulting in an increase in leakage currents during wet conditions which can lead to dry band arcing and potentially flashover (Reference 19).

3.1.3 MPR Analysis

Airborne dust/dirt in the DCPP Unit 2 MBT transformer area, where the ABB surge arresters are located, is a contributor to the flashover events. While similar levels of dust/dirt are undoubtedly

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also present in the Unit 1 MBT switchyard, the prevailing wind for Unit 1 largely blows this debris away from its switchyard. Whereas, the circulating wind patterns present in the Unit 2 MBT switchyard blows it onto the equipment (see Figure 3-1).

Figure 3-1. Prevailing Winds in DCPP Unit 1 and 2 Transformer Yards

3.2 EDG EXHAUST HYDROCARBONS

3.2.1 Insight from Professional/Academia Publications

Airborne dirt, dust, and other industrial airborne contamination [such as hydrocarbons] can cause aging and degradation of the polymers (Reference 15). This is recognized to the extent that the joint Electricite de France (EDF) and ABB Pollution Test Station is located on the coast of southern France (Martigues) near an industrial area that includes an oil-fired power plant, steel industries, and oil refineries (Reference 20). Accordingly, airborne hydrocarbons are a part of the airborne contamination which accumulates on the equipment under test (five test article varieties of ABB surge arresters in this particular paper). In the testing described in Reference 20, the first surge arrester flashover took place in September, during the first rainfall after a long dry period (page 447), which is consistent with the recent DCPP Unit 2 flashover experience.

3.2.2 Insight from PG&E Documentation or Legacy Experience

In Reference 21, PG&E (Bates) states that the DCPP Unit 1 emergency diesel generator (EDG) exhaust stacks go up to the top of the turbine building, about 100-feet above the ground, such that the prevailing winds carry the EDG exhaust well away from the Unit 1 transformer yard. Whereas, the Unit 2 EDG exhaust stacks come out of the Turbine Building about 25-feet above the ground and point horizontally south. The prevailing winds carry the Unit 2 EDG exhaust toward the Unit 2 transformer yard equipment (engulfing them), including the 500kV Lightning Arresters (LAs).

DCPP reviewed the pattern of Unit 2 EDG starts to determine potential effects on insulators in the Unit 2 MBT transformer area. Observations during diesel starting found that the predominant wind from the west typically blows the large amount of visible soot directly over the A and B phase MBT bushings, CCVTs, and LAs (Reference 22).

Following the Unit 2 CCVT flashover (October 11, 2012) swipe samples were taken of the A phase CCVT, LA, and MBT bushing insulator surfaces. The samples indicated high levels of salts, chlorides, and hydrocarbons of both motor oil and diesel content (Reference 22). Also, this same DCPP report (page 47 of 59) identified that multiple ARs and SAPNs document EDG exhaust contamination in the Unit 2 electrical switchgear rooms located at the 85-foot and 119-foot level, respectively.

In a separate expert consultant report prepared following the Unit 2 B Phase LA failure (February 2, 2014), ArresterWorks (J. Woodworth) identified that "The diesel engine exhaust clearly added undesirable contamination in addition to the already heavy salt contamination from the ocean (Pertinent Fact No. 9, Reference 23). Figure 3-2 is excerpted from this same report.

Figure 3-2. Close-up of Unit 2 "B" Phase Lightning Arrester Silicone Rubber Sheds

In a separate expert consultant report prepared following the Unit 2 B Phase LA failure (February 2, 2014), Exponent Failure Analysis (I. Kerszenbaum) also photographed one of the affected DCPP lightning arresters that were returned to the vendor (ABB) for investigation (Reference 24). Figure 3-3 (below) clearly shows the black soot particles contaminating the silicon rubber sheds, which was excerpted from this same report. Note that the soot particles are preferentially deposited on the innermost areas of the sheds (the areas of highest electric field strength). This results from the attractive dielectrophoretic forces arising from the insulator's electric fields acting on the soot particles to cause this preferential deposition.

Figure 3-3. Hydrocarbon Pollution on the DCPP Unit 2 Lightning Arrester Returned to ABB

A DCPP RCE Report (Reference 18, page 27) identified that Unit 1 CCVTs have exhibited electrical tracking. Specifically, following a prescribed burn to reduce dry brush north of the plant (which implies a heavy insulator contamination with hydrocarbons arising from smoke/soot), visible tracking was observed on both the CCVTs and LAs in Unit 1 during rain in the first half of December 2012.

3.2.3 MPR Analysis

Unit 2 EDG exhaust stacks blowing exhaust onto the DCPP Unit 2 MBT transformer area (where the ABB surge arresters are also located), is a contributor to the flashover events. The configuration of the Unit 1 EDG exhaust stacks satisfactorily mitigates this issue for the Unit 1MBT switchyard, in that its exhaust is released at a much greater height (75 feet higher) and blows away from its associated switchyard. However, the circulating wind patterns present in the Unit 2 MBT switchyard blows the Unit 2 EDG exhaust in a way that envelops the Unit 2 equipment.

3.3 LOCAL WEATHER

3.3.1 Insight from Professional/Academia Publications

In a paper focused on hot washing of HV insulators (Reference 25), the PG&E author describes the environment around DCPP as having little rain for approximately eight months during summer and fall months, when contaminants can accumulate. There is also a period of heavy coastal fogs that can further aid contaminant buildup.

In describing EDF and ABB outdoor test facilities for testing ZnO surge arresters in polluted conditions (Reference 20, page 448), a coastal facility located on the south coast of Norway (Lista) having heavy salt pollution and a predominant wind direction is presented. The EDF and ABB authors cite that "dry windy periods followed by fog are the most severe situation from a [surge suppressor] pollution point of view." Later in the report, the authors state that the first surge suppressor flashover during their testing took place during the month of September during the first rainfall after a long dry period. MPR notes that this testing experience closely mirrors DCPP in-service experience.

In describing the aging of polymeric HV insulators outdoors in Mexico (Reference 26), the authors cited that polymer insulators that were installed in service under very heavily polluted conditions lost their excellent hydrophobic properties after being subjected to pollution and wetting, which led to insulator degradation by surface arcing and tracking.

3.3.2 Insight from PG&E Documentation or Legacy Experience

A DCPP RCE Report (Reference 18, page 27) states that DCPP has a long history of insulators exhibiting arcing electrical tracking, dry band arcing, and corona discharge. Measures in place to prevent flashovers include hot washing of insulators and applying silicone grease to porcelain insulators to improve their contamination loading capability. The DCPP RCE Report also says that about a half-hour prior to the [Unit 2 A-Phase CCVT] flashover, witnesses observed visible arcing on the A and B phase CCVTs during the first rain of the season (about 0.9-inches of rain on October 10-11, 2012). A follow-on report (Reference 19, page 22) identified that Unit 1 CCVTs [when their insulator creepage distance was 400-inches] exhibited electrical tracking which reinforced the belief that flashovers have been narrowly avoided with those under-sized insulators, and visible tracking was observed on both the CCVTs and LAs in Unit 1 during rain in the first half of December 2012 following a prescribed burn north of the plant.

A DCPP RCE Report (Reference 19, page 9) states that weather plays an important role in the buildup of contamination on LAs. DCPP experiences cyclical periods of wetting and drying. These cyclical wet/dry periods are due to morning fog followed by an afternoon of drying. The close proximity of the wet/dry cycles causes contamination to be deposited on LAs without any cleansing properties. The lack of periodic rainfall facilitates the increase of external contamination. This report expands on Reference 18 (page 27) citing that while measures previously in place to prevent flashovers were effective it appears that on multiple occasions flashovers were narrowly avoided. This report further cites that a 2009 arcing event was induced by the first significant rain of the fall season mixed with high contamination from wildfires over a long dry spell during the summer.

A DCPP consultant report (Reference 23, pages 3 and 4) cites two weather-related "pertinent facts" concerning the DCPP LA flashovers, one which notes that both DCPP arrester failures occurred during wet events, and the second which notes that because of the daily fog, the arrester housings are wet almost every day for several hours.

Another DCPP consultant report (Reference 24, page 17) included an illustration showing the unbalance between electric fields and voltages inside and outside the arrester due to heavy contamination plus moisture, which results in surface discharges and tracking. This report also cites an ABB service handbook which states that in addition to electric stress, [contaminated] surge arresters are also exposed to substantial thermal stress. Specifically, sizable temperature increase is caused by normal duty operation and external voltage redistribution due to pollution or salt contamination with rain or fog (Reference 27).

The DCPP surge arrester manufacturer (ABB) investigation report (Reference 28) states that DCPP historically is known for the very heavy pollution conditions to which the equipment at the site is exposed, due to the close proximity to the Pacific Ocean, about 100 meters away. ABB further stated that the Unit 2 arrester sheds were found to have a large amount of salt contamination, similar to the Phase B and C LAs inspected earlier.

In a separate inspection report (Reference 29), ABB states that all the [polymer] housings were covered with high salt settlements as pollutants. These were tested with water and the material dissolved in water. When the contamination was removed, the hydrophobic property [of the polymer housings] returned to a high level. ABB states that there was consensus that the heavy pollution was to the left of the [LA] exhaust port, while the tracking marks were to the right of the exhaust port. MPR notes this is therefore indicative of highly non-uniform deposition of contamination. ABB further states that this pattern could be created by the wind tunnel effect by a predominant wind from the northwest swirling within the equipment yard and settling in the observed pattern. ABB also cites in the Reference 29 report that the DCPP choice of the particular Lightning Arrester was a good one, since the outer insulation is specifically designed for coastal application such as DCPP (tested in salt fog per the IEC 60507 standard).

3.3.3 MPR Analysis

The local weather at DCPP imposes severe stresses on the installed HV lightning arresters. Specifically, there are long periods of dry weather, and highly-infrequent rain which greatly restricts the normal outdoor cleansing mechanism (periodic rainfall). Also, there is regular (daily) cyclic fog-wetting and afternoon drying, which greatly aids the heavy buildup of contaminants on the insulators. Lastly, there are strong prevailing winds which act to create non-uniform deposition of contaminants on the insulators, which leads to greater voltage unbalances and surface discharges in regions of deposition gradients. This increases the probability of in-service flashovers. The DCPP local weather environment is precluding the normal surge arrester cleansing mechanisms and is therefore a contributor to the flashover events.

3.4 NON-UNIFORM DEPOSITION OF POLLUTION ON INSULATOR SHEDS

3.4.1 Insight from Professional/Academia Publications

While experimental and in-service experience show that non-uniform deposition of pollution, and surface discharging can occur, the current IEEE C62.11, and equivalent IEC standards (IEC 61109 and 62217), do not address the potential for non-uniform contamination coverage of the outside surface of the insulator (which can promote the generation of radial differential voltage profiles) (Reference 30).

The emerging importance of investigating and characterizing wind-blown non-uniform deposition of heavy pollution on polymer insulators has prompted a variety of outdoor test facilities situated in windy locations. These facilities include the Koeberg Insulator Pollution Test Station on the coast of South Africa (dry summers, high winds, mist banks, and heavy marine and industrial pollution, Reference 30), an EDF/ABB test facility on the coast of southern France (long dry summer, with strong prevailing winds, Reference 2017), and the PG&E field exposure test facility (Moss Landing, California) which included a wind tunnel (Reference 17).

Regarding the wind tunnel testing at Moss Landing, California (Reference 17), the PG&E authors cited production of insulator contamination levels and [non-uniform, windblown] distributions in a few hours that resemble natural contamination found after insulators have been constantly energized in the field for several months. Specifically, non-uniform windblown contamination distributions do not resemble typical laboratory test [salt fog chamber] uniformly deposited insulator contamination.

Another published paper (Reference 31) examined silicone rubber insulators after 15 years of service on a coastal 400kV transmission line in the UK. These insulators were installed by the south coast of England, with prevailing southwest winds and high atmospheric salt and moisture levels. The insulators were found to have aged non-uniformly around their shed circumference. This non-uniformity is shown in Figures 3-4 and 3-5 excerpted from Reference 31.

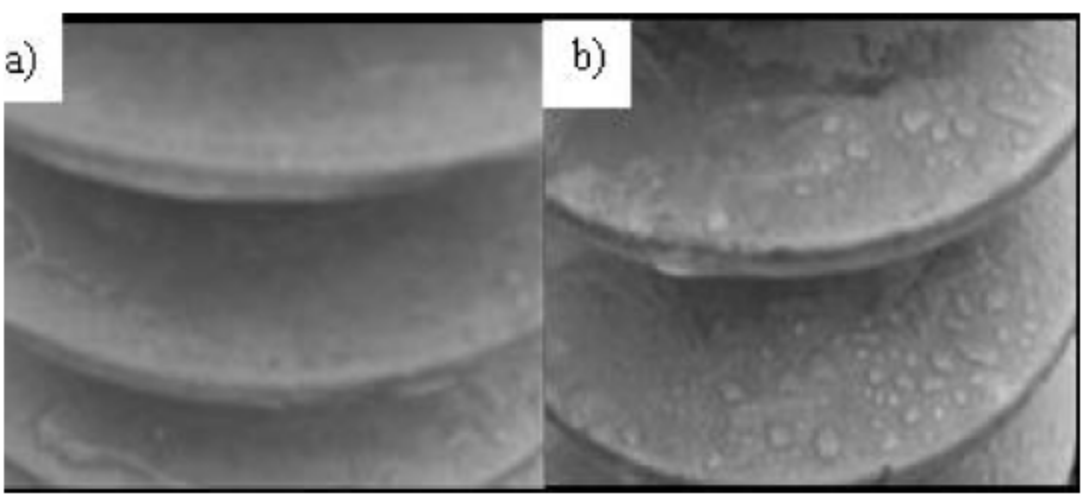

Figure 3-4. Two photos of the same insulator illustrating water droplet formation on the: a) hydrophilic south side, and b) hydrophobic north side

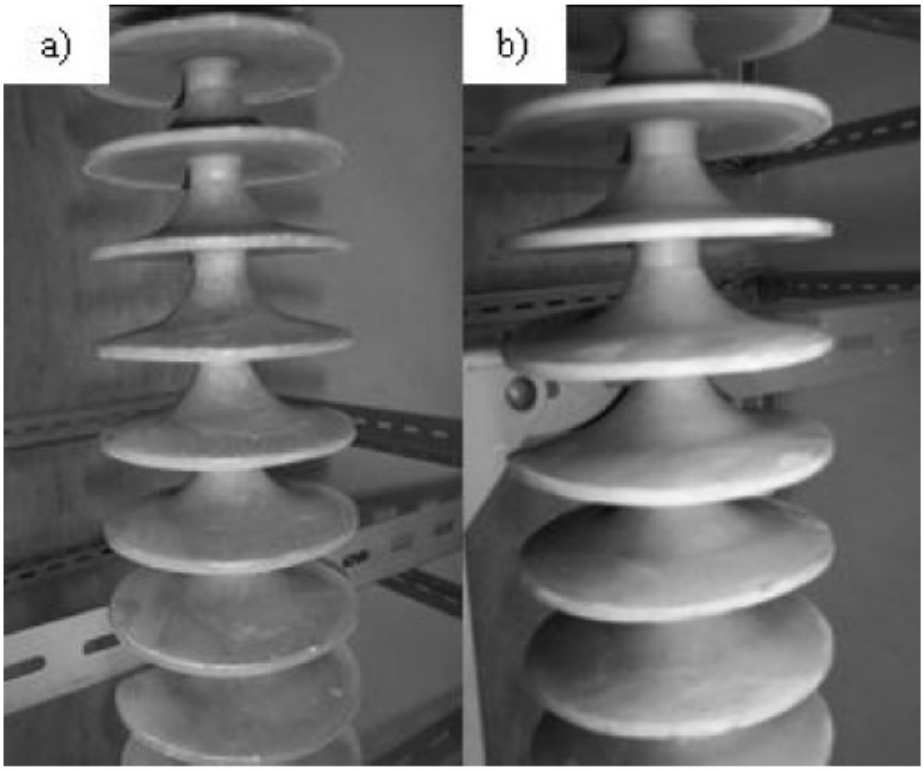

Figure 3-5. Two photos of the same insulator: a) the dirtier north-facing side, and b) the cleaner south-facing side

3.4.2 Insight from PG&E Documentation or Legacy Experience

A DCPP RCE Report (Reference 10, page 15) describes the location of the Unit 2 transformer yard (east of the south end of the Turbine Building and to the northeast side of the Administration Building) citing that a wind tunnel effect is created due to the proximity of these two buildings. As a result, contamination could be deposited unevenly on the [Unit 2] LAs due to the wind pattern. Later in that same report, the most plausible cause of the lightning arrester flashover is "asymmetric deposition of extra-heavy levels of contamination on the LA resulting in uneven voltage gradients".

The LA vendor (ABB) investigation report of the Unit 2 Phase B LA flashover (Reference 29) identifies consensus that heavy pollution was very non-uniform (page 25) and consistently located [on all sheds] to the left of the exhaust port, while bleached electrical tracking were to the right. This pattern could be created by the wind tunnel effect by a predominant wind from the Northeast swirling within the equipment yard settling in a pattern described above (page 20).

A DCPP consultant (McQuinn) report concerning the Phase B LA flashover (Reference 32) identifies non-uniform surface contamination deposits on the LA samples that are oriented in relation to the prevailing wind conditions, along with surface discharging and tracking. McQuinn further states that all of the Unit 2, Phase A & C LA housings showed contamination deposits oriented circumferentially consistent with the prevailing wind direction [at DCPP]. McQuinn also cites that investigation confirms that the cleanest surface conditions were found

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on the windward side, where the surface airflow conditions will preferentially move surface deposits away from the greatest incoming impact pressure areas. The lowest impact area is on the leeward side of the housing, which has the highest deposit accumulations. The majority of surface discharging and tracking were at the quadrature positions, where there is the greatest variation in contamination deposition levels, which suggests that the [highest gradient in contamination] is important to promoting the arcing and tracking conditions. The report provides photos showing this non-uniform deposition of pollution on the failed Phase B LA, one of which is shown below in Figure 3-6.

As found above on the sister unit #2, phase A & C, the phase-B housings also showed clear external contamination deposits, which were oriented circumferentially in sympathy with the prevailing wind direction at the sub-station installation.

Again the heaviest surface deposits were found on the leeward side at the NW position, with heavy surface discharging and continuous streamer activity at the quadrature position of the NE orientation.

Figure 3-6. Excerpt from DCPP Consultant (McQuinn) Report of the Failed Unit 2 Phase B Lightning Arrester Describing Non-Uniform Deposits and Surface Arcing

Lastly, the Reference 33 DCPP report cites that local wind contributed to the hot-wash-induced flashover by blowing a significant amount of water spray back towards the hot wash truck and onto the lightning arrester, rather than falling straight down like previous [washing of porcelain dead-end] insulators. The lightning arrester vendor investigation report (Reference 28) also cites that wind driven pollution from the hot wash process reduced the dielectric insulation air gap strength in the vicinity of the Phase A arrester causing an external flashover.

3.4.3 MPR Analysis

The effect of prevailing wind blowing consistently from one particular direction can affect the deposition of pollution on the LA insulation sheds, causing an asymmetric deposition around the insulator circumference. The resulting deposition gradients can cause non-uniform electric fields and (when dry) influence the dielectrophoretic forces acting on the airborne pollution particles to further accentuate preferential deposition. The same non-uniform electric fields (when wet) lead to early dry-band arcing and eventually a flashover. MPR concludes that the prevailing wind is a contributor to the flashover events.

3.5 SURGE ARRESTER ORIENTATION

3.5.1 Insight from Professional/Academia Publications

Vertical [oriented] insulators do not wash well in the rain because of the sheltering effects of the insulator skirts. Contaminants will tend to remain on the underside of the insulator [sheds] which is not immune from the moistening effects of fog or windblown contaminants. Horizontally oriented insulators have their undersides more thoroughly washed by the rain and therefore tend to fare better than vertical insulators in contaminated areas. Another advantage of insulators in non-vertical positions is that any [hot buoyant] ionized gases caused by arcing will not contribute to setting up conditions where an arc could jump from one [shed] to another or along the skirts of a vertical [multi-shed insulator] (Reference 34).

Investigation of the effects of water droplets on the electric field distribution on the surface of HV polymer insulators identified that the increase in electric fields is considerable [relative to dry conditions] and can reach values that cause corona (Reference 35). The actual bridging of insulator sheds by water droplets also occurs, the potential for which is illustrated in Figure 3-7.

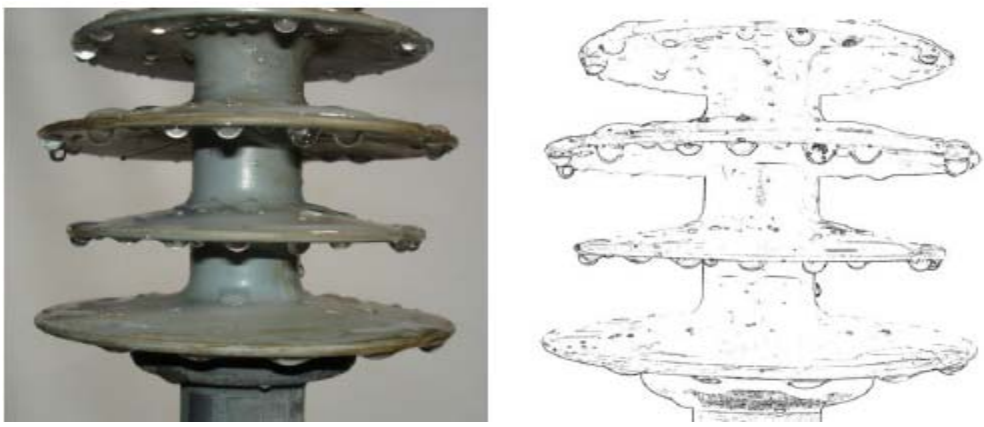

Figure 3-7. Depiction of Water Droplets Which Can Increase Local Electric Fields and Bridge Insulator Sheds

High-speed photos from experiments that focused on the flashover mechanisms of contaminated polymer outdoor insulators under wet conditions, shows actual shed bridging in Figure 3-8 below. The experiments demonstrated that flashover of contaminated insulators can occur during rain at a much lower contamination severity than with fog [in part due to the rain-induced bridging of insulator sheds] (Reference 36).

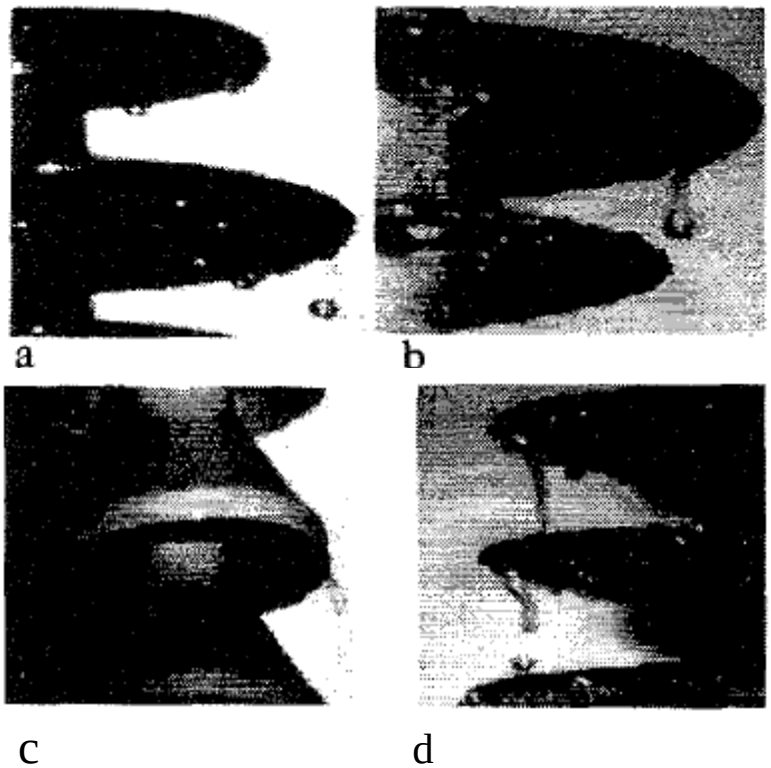

Figure 3-8. Water Droplets Bridging Insulator Sheds During Testing of HV Insulators
Photo "a" shows a hydrophobic surface, photo "b" shows increased bridging from a hydrophilic surface from water pendants, photo "c" shows bridging from a high-angle shed, and photo "d" shows increased bridging from a low-angle shed.

If there is a continuous supply of water drops, as in the case of rain, a large number of pendant water drops of increased volume can aid in forming a continuous water channel. Such a water channel would tend to bridge the air gap between [insulator sheds] (Reference 36).

3.5.2 Insight from PG&E Documentation or Legacy Experience

MPR found no discussion of LA insulator shed orientation in the reviewed DCPP documentation.

3.5.3 MPR Analysis

From the experimental results summarized above, reorienting the DCPP Unit 2 lightning arrestors horizontally would improve their resilience to wet, rain-induced flashovers during periods of heavy insulator contamination. Unfortunately, the basic construction of modern polymer insulated lightning arresters does not permit this to be done. Specifically, the fiberglass tube that comprises the central mechanical support of the lightning arrester is not strong enough to support horizontal, cantilevered orientation of the lengthy arrester.

4 Commonality Between Flashover Events

MPR reviewed the circumstances involved with each of the three recent DCPP flashover events, and finds the following commonality between the events.

Table 4-1. Commonality Between the DCPP Flashover Events

	COMMON ASPECTS OF THE THREE DCPP FLASHOVERS	EXTENT OF COMMONALITY
1	Heavy Salt Contamination Buildup on Lightning Arrester Insulator Sheds	All Three Events
2	Non-Uniform Deposition of Contamination on Insulator Sheds, Leading to Non-Uniform Surface Discharges and Tracking	All Three Events
3	Presence of EDG Exhaust Contamination on Lightning Arrester Insulator Sheds	All Three Events
4	A Rain or Rain-Like Event Which Followed an Extended Period of Dry Weather (empirically proves that rain or rain-like event is worse than fog)	All Three Events
5	Silicone Rubber Insulator Technology Used for Lightning Arrester Insulator Sheds	All Three Events
6	Event Did Not Involve Actual Overvoltage Conditions	All Three Events
7	Event Involve High Voltage Equipment Located in the DCPP Unit 2 Main Transformer Yard	All Three Events

5 Surge Arrester Technology Observations

MPR investigated surge arrester and HV insulator technology to determine whether there are design modifications which could be implemented at DCPP to improve the resilience of these devices to the environmental stresses present at DCPP.

5.1 Surge Arrester Shed Re-Design

5.1.1 Insight from Professional/Academia Publications

The mechanism of contamination flashover due to rain is inherently different from that due to fog condensation. Testing demonstrated that flashover of contaminated insulators can occur with rain at a much lower contamination severity than with fog (Reference 36). This is due to highly non-uniform voltage distributions, and arc bridging between sheds during rain caused by droplet pendants extending from the sheds, as depicted earlier in Figures 3-7 and 3-8, respectively. In the case of condensation-based wetting, discharges along the surface of the insulators are dominant. The Reference 36 study examined new insulator shed shapes aimed at improving contamination performance under rain while maintaining superior fog behavior. Figure 5-1 shows the new polymer insulator profiles that aim at improving contamination performance under rainy conditions. Only the dielectric portion of the insulator is shown and not the end fittings, which are the same as on existing insulators.

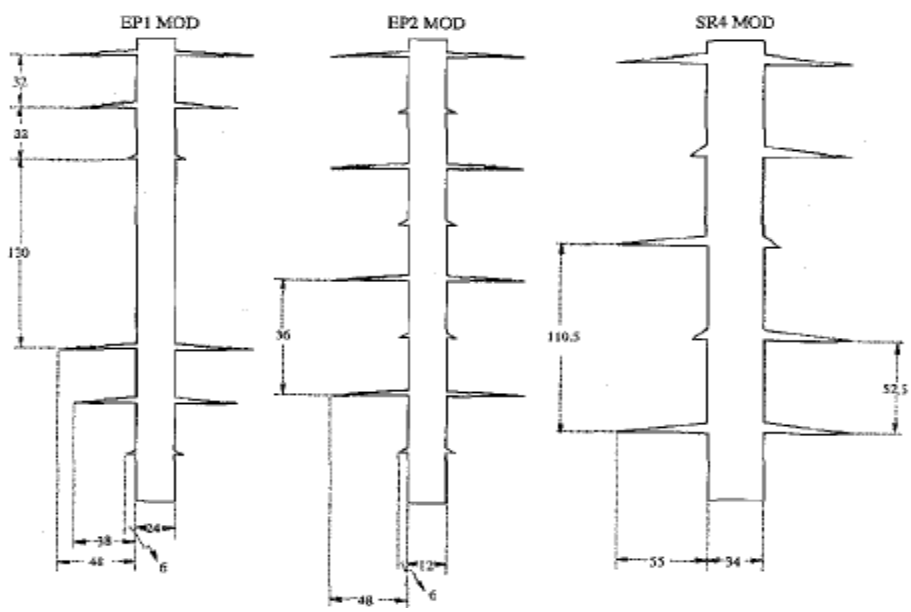

Figure 5-1. Proposed New Polymeric Insulator Profiles Optimized to Improve Performance of Contaminated Insulators Under Rainy Conditions

There are existing insulator shed designs that aim at improving contamination performance under fog conditions, called fog insulators. Given the frequent fog conditions at DCPP, this technology alternative was further examined. Two examples of insulator shed designs described in Reference 37 are optimized to improve contaminated performance in fog conditions, and are shown in Figure 5-2. These designs add under-side ribs to increase overall creepage distance for each insulating shed for the same overall insulator height.

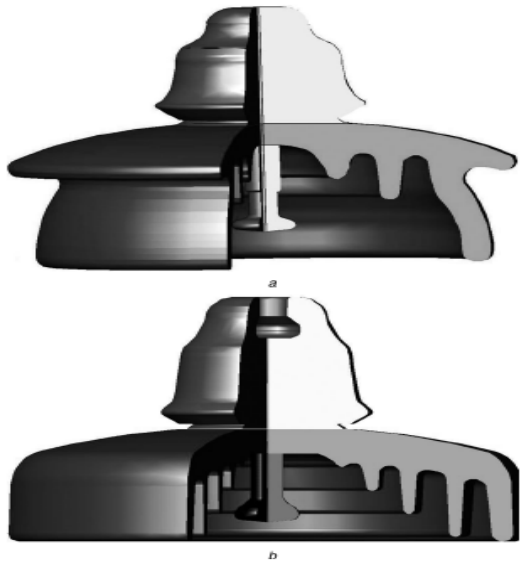

Figure 5-2. HV Insulator Profiles Optimized to Improve Performance of Contaminated Insulators Under Fog Conditions

Fog type insulators were tested in coastal conditions at the Koeberg Insulator Test Station in South Africa and the under-ribs were found to be very effective in suppressing leakage current and of great advantage for reducing the chances of a flashover when installed vertically (Reference 16).

5.1.2 Insight from PG&E Documentation or Legacy Experience

MPR found no discussion of LA insulator shed re-design in the reviewed DCPP documentation.

5.1.3 MPR Analysis

Neither of the re-designed insulator sheds is compatible with the existing manufacturing methods used to construct polymer insulated lightning arresters. The insulating sheds of these devices are extruded onto central hollow shafts. Accordingly, non-uniform shed spacing and under-side ribbing are not possible. Instead, the alternatives of assembling (stacking) several different shed designs, and having sheds with under-side ribbing, are only possible for ceramic or porcelain type HV insulators. The other advantages of polymer insulation for LAs, discussed below, are believed to outweigh this flexibility in shed shaping.

5.2 HV INSULATOR TECHNOLOGY: POLYMER VERSUS PORCELAIN

5.2.1 Insight from Professional/Academia Publications

The consensus of published papers finds polymer-based HV insulators superior to ceramic HV insulators when used outdoors in areas of heavy environmental contamination. This is due to the polymer continuously exuding a layer of silicone that works to encapsulate contaminants on the surface of the insulator. This property allows the insulator to retain hydrophobic surface properties and thereby retard surface discharges, dry banding, and arcing (which lead to flashover). Capturing contaminants in the layer of silicone prevents the buildup of a conductive film when the surface is later exposed to moisture. Specifically, the silicone layer performs the same function as the silicone grease often applied to porcelain insulators to improve their contamination performance and resist flashovers. But a key factor is to keep the polymer surface contamination below that which overwhelms the hydrophobicity (and it reverts to porcelain-like performance).

In addition to being much lighter, less fragile, and not needing careful handling, polymer technology also fails in a less dangerous way. Specifically, Figure 5-3 (Left Side) illustrates how a silicone rubber insulator fails catastrophically (it splits open), while Figure 5-3 (Right Side) illustrates how ceramic insulators can explode and create sharp, dangerous shards.

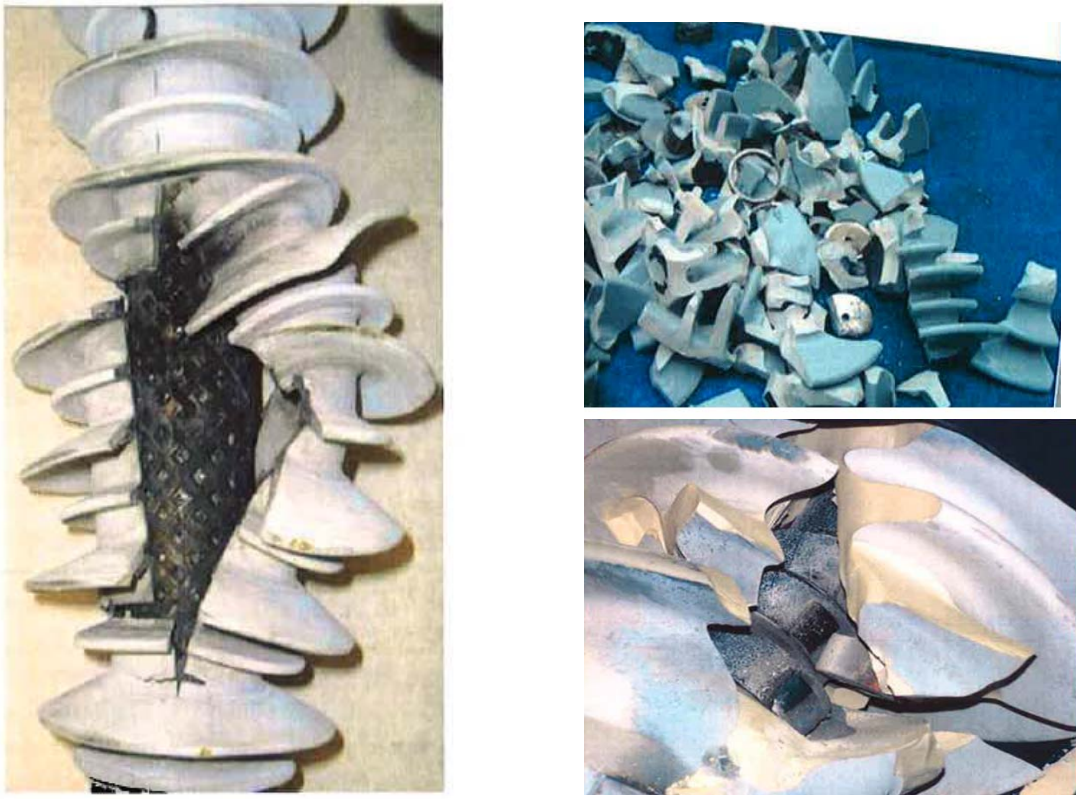

Figure 5-3. Comparison of Catastrophic Failures of Polymer Insulators (Left Side Photo) and Ceramic Insulators (Right Side Photos)

5.2.2 Insight from PG&E Documentation or Legacy Experience

DCPP legacy experience indicates that the previous porcelain surge arresters worked satisfactorily for many years, while the recently installed (in 2009) polymer surge arresters have failed frequently.

However, there is PG&E documentation that identifies that in the region of California where DCPP is located, many contamination flashovers have occurred with porcelain insulators in the substation and transmission lines in the past. This occurred to the extent that energized washing is performed on a routine basis during the dry summer and fall months (Reference 25), and that a PG&E outdoor HV insulator performance test facility (at Moss Landing) was established in part to investigate methods of reducing contaminated porcelain insulator flashovers (Reference 17).

DCPP documentation (Reference 18, page 27) states that DCPP has a long history of [porcelain] insulators exhibiting arcing, electrical tracking, dry band arcing and corona discharge. It further states that the [periodic maintenance] measures previously in place to prevent flashovers were effective, although it appears that on multiple occasions, flashovers were narrowly avoided. The measures in place [at DCPP] to prevent flashovers include periodic hot washing of insulators and applying silicon grease to porcelain insulators to improve their contamination loading capability (Reference 18). The porcelain high voltage bushing failure event which precipitated the change to polymer surge arresters at DCPP was not caused by a flashover event. Per Reference 41, the presumptive root cause was for the failure was either an internal degraded test tap connection or low bushing oil level.

One DCPP polymer LA flashover RCE Report (Reference 10, page 29) cites that the polymer insulator material is considered to be the best material in high contamination environments according to both predominate manufacturers.

5.2.3 MPR Analysis

The incentives that convinced DCPP to switch over to polymer insulated surge arresters in 2009 still exist. Returning to porcelain insulator surge arresters would be challenging (not impossible) since the US manufacturers of these devices have ceased production, although a foreign source (Japanese) or arresters obtained from other utilities are still possible.

MPR found references to considerable periodic maintenance (hot washing and applying silicone grease) being routinely done on the legacy DCPP porcelain insulators, including a change to increase the frequency of hot washing (from once every six months) to once to every six weeks. This seems to involve a considerable recurring effort. However, it appears (from the documentation provided to MPR) that little of this preventive maintenance effort carried over after the polymer insulators were installed in the transformer yards in 2009. MPR believes that, in the severe DCPP contamination environment, polymer insulators also need some form of periodic preventive maintenance as well. The empirical in-service experience at DCPP is that, after 2009, insufficient periodic preventive maintenance was done on the polymer insulators.

Based on an international academic consensus, and domestic manufacturer consensus, MPR believes that polymer insulator material is the best HV insulator material in high contamination environments. However, the contamination environment at DCPP appears to be severe enough

to warrant additional mitigating actions beyond the normal practices employed in other high contamination environments.

5.3 INSULATOR COATINGS

Manually applying a layer of silicone grease has been done to porcelain insulators for many years to improve contamination performance and reduce flashovers. When applied, the new grease readily absorbs contaminants that settle on the surface, preventing their dissolution in water droplets (in rain or fog), thereby preventing leakage currents which can lead to flashover. The silicone grease works well in preventing flashover up to the point where the grease becomes saturated with contaminants (Reference 38).

5.3.1 Insight from Professional/Academia Publications

No investigations, testing, or in-service operating experience was found concerning applying silicone grease onto polymer insulators to improve their contamination resilience, as is done for porcelain insulators.

5.3.2 Insight from PG&E Documentation or Legacy Experience

An expert consultant retained by DCPP in early 2014, ArresterWorks (J. Woodworth) recommended applying silicone grease (used for porcelain insulators elsewhere on the DCPP site) on the surge arrester silicone rubber insulators to further improve the surface capture of contaminants (Reference 23, page 9). Woodward stated that a trial experiment on a spare silicone-housed arrester energized at a lower voltage (with a leakage current monitor) should be done first to verify satisfactory performance.

A second expert consultant retained by DCPP in early 2014, EACH Engineering (Dr. Cherney) also suggested applying silicone grease onto the surge arrester silicone rubber insulators to further improve the surface capture of contaminants (Reference 38). Cherney stated that, while there is no known application of silicone grease to non-ceramic insulators, it will perform analogously to grease on ceramic insulators. If removed and re-applied before [contaminant] saturation, silicone grease is a good option to water washing. However, unlike grease applied to porcelain, some of the silicone oil from the grease can be expected to penetrate the silicone rubber housing which may hasten drying out of the grease.

A PG&E test facility (the Applied Technology Services, ATS, group) has commenced testing of the interactions of silicone grease with polymer insulator materials, in support of field application of silicone grease on silicone rubber insulators (Reference 39). The initial test results are promising in that, after 90 days, the percentage of silicone oil in the grease encountered only about 5% absorption into the insulator, with the absorption rate leveling off (Reference 39). This implies that it should remain an effective measure for a useful length of time. However, when contacted by DCPP following the Unit 2 CCTV flashover (October 11, 2012), the surge arrester manufacturer identified that they do not recommend the addition of silicone grease to polymer insulators (Reference 22, page 8).

5.3.3 MPR Analysis

MPR agrees with the two industry expert consultants (ArresterWorks and EACH Engineering) that applying silicon grease to the Lightning Arrester (LA) silicone rubber insulators should further improve the surface capture of contaminants, and thereby improve the resilience of the devices to flashovers caused by the DCPP heavy contamination environment. MPR notes that DCPP has commenced a prudent test program in support of this activity at PG&E-ATS.

Regarding the lack of other industry and academic interest in examining this action, MPR believes that it arises from the vast majority of LA usage (involving service average environmental contamination conditions) being satisfied as-is with off-the-shelf LAs - and only a narrow minority of users with the outlier *very heavy* contamination levels need additional measures such as this.

Completing the PG&E-ATS testing to prove that the silicone grease behaves satisfactorily on polymer insulators is appropriate.

5.4 ENGINEERED FIXED-NOZZLE WASH EQUIPMENT

5.4.1 Insight from Professional/Academia Publications

Washing HV insulator sheds to remove contamination, often while the conductors are still energized, has been going on for many years. One team of researchers describe a hot, dry California coastal environment (similar to DCPP) and cite that, to prevent flashovers, energized washing is performed on a routine basis during the dry summer and fall months (Reference 25). Reference 25 cites that there occurred an episode where an extreme volume of water from hot wash overspray cascaded across the sheds of contaminated HV insulators resulting in an unintended flashover. Reference 25 further identifies that in response, countermeasures were determined to be effective in avoiding flashover recurrence: (1) reducing the volume of water by using a nozzle with a small orifice, and (2) using a system with a fixed nozzle. Reference 25 further states that fixed spray systems are commonly installed in coastal substations in Japan.

5.4.2 Insight from PG&E Documentation or Legacy Experience

Energized “hot” washing has also been going on at DCPP for many years, arising from a 1996 report of the failure of 500kV dead-end insulators at the PG&E Round Mountain switchyard (Reference 33). In 1998, the hot wash frequency at DCPP was changed from every six months to every six weeks. However, after 93 successful manual hot washes of Unit 2 transformer yard components, personnel errors in the washing evolution resulted in an inadvertent LA flashover and plant trip (July 10, 2012).

DCPP RCE Report of a subsequent Unit 2 B Phase Lightning Arrester flashover (Reference 19) included as a Prudent Action (PA-1) determining the feasibility of installing an artificial rain/deluge system to remove contamination from the LAs.

DCPP expert consultant (EACH Engineering) in March 2014 recommended using a fix-mounted atomized spray system to supplement natural rain conditions, especially in prolonged drought

conditions. Such systems have been known to be used on similar energized HV sub-station installations, for both LA housing and standoff insulator components, without the risk of back-splash flashover events (Reference 38).

The LA vendor (ABB) investigation report accomplished following the Unit 2 B Phase Lightning Arrester flashover (Reference 29) recommended that DCPP install an artificial rain system to aid the [LA] silicone's natural hydrophobic properties to be extended through the drought periods experienced in [the DCPP area] and that may occur into the future.

5.4.3 MPR Analysis

The majority of the common factors associated with all three recent flashover events at DCPP involved the presence of heavy contamination on the polymer insulator sheds. The most effective solution for precluding future Unit 2 flashovers involves keeping these insulators clean. Given that forensic sampling of DCPP failed LAs by the LA vendor determined that the heavy contamination they found is water soluble, and that periodic cleansing rain cannot be counted on at DCPP, an engineered fixed nozzle water deluge spray system designed to preclude causing flashovers should be considered.

Since a key factor in the personnel errors committed in the hot-washing evolution that resulted in an inadvertent LA flashover (July 10, 2012) was inattentiveness to Unit 2 wind conditions, MPR considers that, if hotwashing of MBT and/or LAs are ever considered in the future, clear procedural requirements regarding acceptable wind conditions should be a required condition for initiating and continuing a hot wash evolution at Unit 2.

A commercial source of site-custom water deluge spray equipment especially intended for hot-washing HV insulators and LAs was identified (Reference 40). This established company's equipment uses fixed atomizing spray nozzles (located at the base of each LA) which are aligned to avoid inappropriate overspray. Company photographs depict their wash deluge equipment in service cleaning LAs similar to those installed in DCPP.

5.5 SURGE ARRESTER MONITORING

5.5.1 Insight from Professional/Academia Publications

Attributes that can be monitored and used to assess the health of a polymer insulated surge arrester include: (a) leakage current, (b) insulator surface temperature, (c) surface arcing presence and color, and (d) sampling of surface contaminants.

5.5.2 Insight from PG&E Documentation or Legacy Experience

DCPP documentation does not identify that there are any leakage current monitors on the Unit 2 500kV surge arresters. Similarly, there is no discussion of any thermal monitoring of the surge arresters.

Regarding monitoring insulator surface dry band arcing, Reference 38 states that yellow-color dry-band arcing is serious but not indicative of imminent problems, but if it progresses to "white" arc stage, then a flashover can occur soon. A DCPP RCE Report (Reference 18)

describes a [porcelain dead-end insulator] monitoring approach where visual arcing (yellow/orange in color) spanning one or more sheds across the length of the insulator occurring during the first rain after a dry spell should be a trigger point of a condition-based maintenance strategy.

Regarding contamination monitoring, a DCPP RCE report states that manual swipe based monitoring should be established for Unit 2 transformer yard insulators (Reference 18).

5.5.3 MPR Analysis

Potential parameters that should be considered for monitoring the in-service health of the Unit 2 Las include:

- Leakage Current – Leakage current monitoring was done previously at DCPP on the 230KV system.
- Infrared (IR) Imaging Based Temperature Monitoring – IR imaging based monitoring of the LA insulator surface temperature can help assess the amount surface discharge arcing is occurring.
- Visual Arc Assessment – This would include assessing the extent and coloration of visually-observable LA arcing, and under what ambient environmental conditions they are occurring.
- Contamination Sampling – This would include periodic sampling of the contamination accumulating on the Unit 2 LAs and should include a separate (spare) arrester mounted in the yard in proximity to the in-service units to serve as a control sample.

In all cases, clear acceptance criteria should be established for actions to take to prevent flashover events from occurring.

6 Additional Observations

6.1 Polymer Contamination Testing

In reviewing professional and academic publications, and IEEE and IEC testing standards and creepage guidance, MPR observes that the bulk of this data falls into two camps. The first camp encompasses researchers and experimentalists whose published results clearly identify that the worst outdoor contamination environments involve proximity to the seacoast and sources of industrial pollution, extended hot dry weather interspersed with high-moisture fog followed by heavy rains, while having constant, strong, unidirectional prevailing winds. This worst-case environment deposits very heavy contamination onto HV insulators in a highly non-uniform manner, which is capable of rapidly creating flashover conditions.

The second camp encompasses the IEEE/IEC Standards professionals, and the salt fog chamber testers who deal exclusively with uniformly-deposited contamination. These second-camp groups combine to create standards and guidance for setting satisfactory insulator creepage distances based on non-realistic uniformly-deposited contamination, but which under-specify creepage distances for those activities which experience more onerous non-uniformly deposited contamination (like DCPP). Unfortunately, MPR has not identified any IEEE/IEC consensus to better address non-uniformly deposited contamination. The end result is that those users at the extreme end of contamination deposition condition (like DCPP) are left to simply add their own "length conservatism" to the standard creepage distance standards guidance.

6.2 Further Quantifying Local Environmental Conditions

MPR believes that the local environmental conditions at DCPP, which include proximity to the seacoast and sources of EDG exhaust and dust and wildfire pollution, extended periods of hot dry weather interspersed with high-moisture fog followed by heavy rains, while having strong unidirectional prevailing winds comprises a small-percentage "outlier" position relative to the rest of the LA user community.

Unfortunately, the above noted environment deposits very heavy contamination onto HV insulators in a highly non-uniform manner, which is not properly addressed by existing Standards guidance based on uniformly-deposited contamination.

The single influencing environmental factor that adversely impacts the DCPP Unit 2 LAs is the non-uniform deposition of the contamination on the insulator sheds, which leads to contamination gradients and early surface discharge activity. The divergence between the Unit 1 flashover in-service experience (not much) and the Unit 2 flashover experience (excessive) highlights this factor which results from the Unit 2 wind patterns. Additional work to quantify the DCPP environmental conditions is important. Based on a review of available modeling techniques, MPR concludes that it is feasible to use computational fluid dynamics (CFD) modeling to characterize the impact of the building arrangement at DCPP on the local wind

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conditions near the LAs for Units 1 and 2. Dimensional information (length, width, and height) of each building and the transformer yard structures will be required. Meteorological data (e.g., wind speed and direction) for the site will also be needed.

Based on the local wind speed determined from the CFD and other conditions of the LAs, the equivalent salt deposit density (ESDD) for each area arising from non-uniform deposition can be better estimated. This analysis can demonstrate how the local wind conditions contribute to the failures of the Unit 2 lightening arrestors.

7 Conclusions

MPR analyzed the expert evaluations, professional and academic publications, root cause analyses, extent of condition reports, legacy PG&E experience documentation, and the design and material of the affected components for the three recent DCPP Unit 2 switchyard events. MPR reached the following conclusions:

7.1 Commonality Between Three Flashover Events

MPR's analysis of the commonalities for three recent DCPP Unit 2 flashover events is summarized in Table 4-1. We conclude there is commonality between the events. Specifically, the common elements of the events include:

- Very heavy, non-uniform contamination present on the insulator sheds, and
- Rain (or rain-like conditions) following an extended period of dry weather.

7.2 Relative Impact of Rain Versus Fog Wetting

As discussed in Section 3.5, research experimentation demonstrates that flashover of contaminated insulators can occur during rain at a much lower contamination severity than with fog [in part due to the rain-induced bridging of insulator sheds] (Reference 386). From a flashover standpoint, rain is worse than fog. This correlates with the DCPP Unit 2 in-service flashover experience where all three events occurred during rain or rain-like events (e.g., misdirected hot washing sprays). The Unit 2 experience with fog wetting of insulators is that the repeated sequence of morning fog followed by afternoon drying acts to build up layers of contamination.

7.3 Unit 2 Topology a Factor

As discussed in Table 4-1, all three flashovers occurred at Unit 2. There are distinct differences in the size, orientation, and spacing of structures surrounding the Unit 2 transformer yard versus those surrounding the Unit 1 transformer yard. These surrounding structures affect the wind and air flow patterns around the HV bushings and insulators, causing differences in the deposit rate of contaminants, with the local environment of Unit 2 being the worst. We note that the Unit 1 CCVTs have exhibited electrical tracking and visible tracking was observed on both the CCVTs and LAs in Unit 1 during rain in the first half of December 2012 following a prescribed burn north of the plant (Reference 18, page 27).

7.4 Gap Between in Industry Type Tests Versus Actual Field Performance

Field service conditions that include the exposure of surge arresters, insulators, and bushings to damaging fumes, vapors, steam, salt spray, or excessive amounts of contamination require

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special considerations and are classified as "Unusual Service Conditions" by industry standards. Arresters failed were classified for heavy. However, some industry literature suggests that there is not a good correlation between environmental conditions simulated in type tests and actual field performance. Therefore, special tests performed to "qualify" suitable insulators and arresters for DCPP may be required.

7.5 Contamination Constituents and Deposition Rates Are Not Quantified

MPR concludes that the in-situ insulator contamination constituents and deposition rates at DCPP are not well quantified. Understanding the constituents' composition and deposition rate will provide a basis for selecting suitable replacement equipment or determining the appropriate mitigation strategies to employ. MPR also concludes that the relative importance of the various contaminants present at DCPP (e.g., dirt, salt, and EDG combustion byproducts) is not well understood with respect to which are key drivers that lead to flashover events and in what quantities do they become key drivers.

7.6 Non-Uniform Contamination Is a Challenging Outlier Condition

Industry standards for contaminated insulator creepage distances are based primarily on type testing of insulators with uniformly deposited contamination. As discussed in Section 3.4, research investigation also shows that non-uniform deposition of contamination on insulator sheds (as occurs in the Unit 2 MBT switchyard) facilitates greater surface arcing, tracking, and early flashover (References 30 and 31). Quantifying this adverse effect is challenging, since it requires expensive test facilities and techniques, and is an "outlier condition" that is not applicable to the majority of HV insulator users. PG&E previously invested in such test facilities and research (Reference 17), but the test results have languished due to outdated computer tools used and personnel retirements.

As discussed in Section 3.4, research into non-uniform deposition of heavy contamination shows this condition to be conducive to heavy surface arcing, tracking, and early flashover. These findings correlate with the empirical, in-service operating experience of the Unit 1 and Unit 2 transformer yard components.

Today, few alternatives, standards, or guidance exist to offset the adverse effect of non-uniform deposition of contamination. The primary design feature available to offset it is to conservatively increase the insulator's length (creepage distance) beyond the normal contamination rating, but there is little guidance or assurance as to how much is sufficient for DCPP's "outlier" conditions. Selecting "extra heavy" contaminant rated creepage distance would add margin, but there is little technical basis that this margin (alone) will preclude future flashovers. Therefore, MPR concludes that a better understanding of the contamination constituents, their distribution and deposition rates is required to properly establish the in-service functional requirements for the equipment.

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7.7 CFD MODELING

It is feasible to use computation fluid dynamics (CFD) modeling to characterize the impact of the building arrangement at Diablo Canyon site on the local wind conditions near the lightening arrestors for Units 1 and 2. Based on the local wind speed determined from the CFD and other conditions of the surge arresters, the equivalent salt deposit density (ESDD) levels for each area can be estimated. See Section 6.2 of this report.

7.8 PORCELAIN VERSUS POLYMER INSULATORS AND BUSHINGS

Each of the three recent DCPP Unit 2 flashover events involved silicone rubber polymer insulators. While the incentives that convinced DCPP to switch over to polymer insulated surge arresters in 2009 still exist, the original porcelain insulators and bushings provided many years of satisfactory service at DCPP and the failure of the main electrical transformer "C" phase high voltage porcelain bushing in 2008 was not due to surface contamination (see LER 50-323, 2008-001-00, Reference 41).

Although returning to porcelain insulator surge arresters may be challenging, MPR concludes that this option should be evaluated further.

PG&E legacy documentation cites that in the region of California where DCPP is located, many contamination flashovers occurred with porcelain insulators in the substation and transmission lines in the past. As a result energized washing is performed on a routine basis during the dry summer and fall months (Reference 25), and a PG&E outdoor HV insulator performance test facility (at Moss Landing) was established in part to investigate methods of reducing contaminated porcelain insulator flashovers (Reference 17).

DCPP documentation (Reference 18) states that DCPP has a long history of [porcelain] insulators exhibiting arcing, electrical tracking, dry band arcing and corona discharge. However, the measures previously in place to prevent flashovers were effective, although it appears that on multiple occasions, flashovers were narrowly avoided. The measures in place [at DCPP] to prevent flashovers include hot washing of insulators and applying silicon grease to porcelain insulators to improve their contamination loading capability (Reference 18, page 27).

Regarding the preventive maintenance measures to prevent flashover of porcelain insulators, in 1998, the periodic frequency of PG&E hot washing was increased from once every six months to once every six weeks, presumably to further mitigate flashovers (Reference 33). For the periodic greasing of PG&E porcelain insulators with silicone grease, the periodicity was unclear. In summary, reverting back to porcelain insulators would add some preventive maintenance beyond what was has been done with the DCPP MBT switchyard silicone rubber insulators. The relative risks and benefits of returning to porcelain insulators will require significant evaluation.

7.9 MONITORING OF KEY PARAMETERS

MPR concludes that installation of additional monitoring equipment could help detect trends in the buildup of contaminates before they cause flashovers. As discussed in Section 5.5, the key parameters of interest for closely monitoring the in-service health of the Unit 2 lightning arresters include:

1. Leakage current on the 500 kV LAs, as has been done previously at DCPP on the 230 kV system,

2. Infrared (IR) imaging of the LA insulator surface temperature to help assess the amount surface discharge arcing is occurring,

3. Visual observation of the extent and coloration of LA arcing, and noting ambient environmental conditions that are occurring, and

4. Periodic sampling of the contamination accumulating on the Unit 2 LAs, including on a separate (spare) arrester mounted in the yard in proximity to the in-service units to serve as a control sample.

7.10 DESIGN IMPROVEMENTS

After developing a better understanding of the actual in-service conditions the insulators must be designed for, there are a number of design changes that could be implemented to improve the robustness of the equipment or mitigate the buildup of contaminants. These include:

1. Insulator Coating (Silicone Grease)

   As discussed in Section 5.3, MPR concludes that the PG&E-ATS testing to prove that the silicone grease behaves satisfactorily on polymer insulators should be completed.

2. Installing Arresters with Longer Creep Distances

   Insulators designed for areas subject to industrial smoke that produces thick conductive deposits, or coastal areas exposed to very strong and polluting sea winds, that are classified as suitable for "Extra Heavy" contamination typical are tested to ESDD levels above 0.6 mg/cm^2.

3. Surge Arrester Re-Orientation and Shed Re-Design

   As discussed in Section 3.5, testing shows that re-orienting the LA sheds from the existing vertically stacked configuration to horizontally would greatly improve water cleansing action and reduce flashovers from cascading water pendants. However, the existing LA designs are insufficiently strong to accommodate cantilevered mounting.

   As discussed in Section 5.1, research testing shows that re-designing the LA sheds to utilize Fog Underside Profiles would improve creepage distances for improved wet performance. However, existing LA designs cannot accommodate such alternate shed design with their existing silicone rubber extrusion-based LA manufacturing methods.

4. Engineered Fixed-Nozzle Wash Equipment

   As discussed in Section 5.4, the majority of the common factors associated with all three recent flashover events at DCPP involved the presence of heavy contamination on the insulator sheds. The most effective solution for precluding future Unit 2 flashovers

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involves keeping those insulators clean. Given that forensic sampling of DCPP failed LAs by the LA vendor determined that the heavy contamination is water soluble, and that periodic cleansing rain cannot be counted on at DCPP, a carefully engineered fixed nozzle water deluge spray system which is designed to preclude causing flashovers would greatly mitigate the heavy contamination conditions which cause a flashover.

Since a key factor in the personnel errors committed in the hot-washing evolution that resulted in an inadvertent LA flashover (July 10, 2012) was inattentiveness to Unit 2 wind conditions, clear procedural requirements regarding acceptable wind conditions should be a required condition for initiating and continuing a hot wash evolution at Unit 2.

8 MPR Recommendations

MPR recommends implementing the following recommendations to determine the appropriate corrective action, or combination of actions, that will be successful in precluding future flashovers.

1. Minimize, to the extent practical the generation of airborne dust and dirt onsite.

2. Characterize the insulator contamination constituents and deposition rates by periodically sampling the contamination accumulating on the Unit 2 LAs. Characterization of the contamination constituents should include the types of EDG combustion products being deposited on the insulators. PG&E should measure the concentration of salts in the free flowing fog (this should be used to determine the adequacy of the vendor type testing). PG&E should consider installing a separate (spare) arrester mounted in the yard in close proximity to the in-service units to serve as a control sample.

3. Conduct a series of contaminated insulator breakdown tests to determine the relative importance of the various constituents. These tests should include non-uniformly distributed contaminates. These tests should be structured to reveal which contaminants are the key drivers that lead to flashover events and in what quantities do they become key drivers. The results of these tests should inform the evaluation of alternatives listed in Item #7, below.

4. Develop a CFD model to characterize the impact of the building arrangement at DCPP on the local wind conditions near the lightening arrestors for Units 1 and 2. Such a model will require dimensional information (length, width, and height) of each building and the transformer yard structures. It will also need meteorological data (e.g., wind speed and direction) for the site. Based on the local wind speed determined from the CFD and other conditions of the lightening arrestors, the equivalent salt deposit density (ESDD) for each area can be estimated. The results of the model analyses will determine how the local wind conditions contribute to the buildup of contaminants and failures of the Unit 2 lightening arrestors.

5. Establish the in-service functional performance requirements for the transformer yard bushings and insulators and compare these requirements with the type testing performed by various vendors in accordance with industry standards. Any gaps identified by the comparison establish the need for special qualification tests to satisfy DCPP site specific requirements.

6. Evaluate the feasibility of returning to porcelain insulator surge arresters.

7. Prepare an evaluation of alternatives of mitigating actions that could be implemented to prevent future flashover events. The alternatives analysis should consider the risks and benefits of the following mitigating actions (at a minimum):

- Reduction of dirt and dust through periodic wetting or other techniques
- Altered configuration of Unit 2 EDG exhaust stack
- Wind mitigation techniques (such as engineered wind screens)
- Fixed nozzle wash equipment
- Monitoring key arrester parameters
- Adding silicone grease coating
- Returning to porcelain insulators
- Periodic shutdowns for washing (or hot washing)

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22. Root Cause Evaluation Report 50518473, Revision 2, dated May 2, 2015, page 21 of 59.

23. ArresterWorks (J. Woodworth), “Arrester Failure Root Cause Analysis” prepared for DCPP, dated April 3, 2014, page 4.

24. Exponent Failure Analysis (I Kerszenbaum), “Phase B and C Lightning Arresters Inspection at ABB” prepared for DCPP, dated February 13, 2014, page 6 of 19.

25. R. Sharp (PG&E), S. Yokoi, J. Bernham, “Washing Withstand Voltage Tests on Station Insulators”, IEEE Conference on Transmission and Distribution, October 2001, pages 765-770.

26. R. Hernandez, I. Ramirez, F. Lopez, “Accelerated Aging Test of Non-Ceramic Insulation”, IEEE conference on Electrical Insulation Dielectric Phenomena, 2008, pages 268-271.

27. ABB Service Handbook, third edition, Product Group Service, 2009, page 75.

28. ABB (A. Vitols) Surge Arrester Investigation Report, RMA-804, dated September 1, 2013.

29. ABB (K. Spillar, A. Vitols) Surge Arrester Investigation Report, RMA-829, dated March 14, 2014.

30. J. Seifert, R. Barsch, W. Vosloo, “Dimensioning of the Housing Profile of Silicone Rubber Composite Insulators for Harsh Marine Pollution Conditions, CIGRE, 2008.

31. S. Rowland, Y. Xiong, J. Robertson, and S. Hoffman, “Aging of Silicone Rubber Composite Insulators on 400KV Transmission Lines”, IEEE, 2007, pages 130-136.

32. McQuinn Electrical Power Consulting (N. McQuinn) report, “DCPP Lightning Arrester Inspections”, dated March 16, 2014.

33. DCPP Root Cause Evaluation Report 50573100, Revision 0.1, dated October 24, 2013.

34. Design Manual for HV Transmission Lines, USDA Rural Utilities Service, Bulletin 1724E-200, May 2009, Page 8-8.

35. A. Souza, I. Lopes, “Electric Field Distribution Along the Surface of HV Polymer Insulators and Its Changes Under Service Conditions”, 2006 IEEE International Symposium on Electrical Insulation, 2006, pages 56-59.

36. A. DelaO, R. Gorur, “Flashover of Contaminated Nonceramic Outdoor Insulators in a Wet Atmosphere”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 5 No. 6, December 1998, page 818.

37. K. Siderakis, D. Agoris, J. Stefanakis, “Influence of the Profile on Performance of Insulators Installed in Coastal HV Networks having Condensation Wetting”, IEEE Proceedings of Scientific Measurement Technology, Vol 153, No. 4, July 2006, pages 158-163.

38. EACH Engineering (E. Cherney) report, “Flashover of Unit 2 “A” Phase Silicone Rubber 500KV CCVT”, dated February 27, 2013.

39. PG&E DCPP PowerPoint Presentation, “Lightning Arrester Performance”, provided to MPR by PG&E on April 23, 2014.

40. Wilorton Holding Company, information describing fixed-nozzle hot line insulator equipment, including in-service photographs depicting ABB style lightning arresters being hot washed, www.wilorton.com, Chiasso, Switzerland, 2014.

41. Diablo Canyon Unit 2 Licensee Event Report 50-323/2008-001-00, “Reactor Trip Due to Main Electrical Transformer Failure,” dated October 15, 2008.

B Documentation Reviewed

The following DCPP Unit 2 documentation was reviewed by MPR during this effort:

Diablo Canyon Power Plant Root Cause Evaluation Reports

- Unit 2 "A" Phase CCVT Flashover Results in Unit 2 Trip (RCE Report 50518473, Rev. 2)
- Unit 2 "A" Phase Lightning Arrester Flashover Results in Unit 2 Trip (RCE Report 50573100, Rev. 0.1, with attachments)
- Unit 2 "B" Phase Lightning Arrester Flashover Results in Unit 2 Trip (RCE Report 50607838, Rev. 0)

Diablo Canyon Power Plant Emerging Issue Summary Reports

- Unit 2 "A" Phase Lightning Arrester Flashover (DCPP Report 2Y18, Rev. 7/11/13)
- Unit 2 "B" Phase Lightning Arrester Flashover (DCPP Report Rev. 2/4/14)

Diablo Canyon Power Plant Replacement Part Evaluation Reports

- 500-KV Capacitance-Coupled Voltage Transformers with polymer insulators vice porcelain (RPE Number 8000004621)
- 500-KV Replacement Models of Lightning Arresters (RPE 8000004622)

  Revision 0 – Replace obsolete GE porcelain LAs with ABB polymer LAs

  Revision 1 – Replace ABB polymer LAs with alternate model w/ longer creepage)

Diablo Canyon Power Plant Lightning Arrester Vendor (ABB) Investigation Reports

- ABB, Mount Pleasant, PA (K. Spillar and A. Vitols), "RMA-804 Surge Arrester Investigation Report", dated 8/19/13
- ABB, Mount Pleasant, PA (K. Spillar and A. Vitols), "RMA-829 Surge Arrester Investigation Report", dated 3/14/14

Diablo Canyon Power Plant Expert Consultation Reports

- ArresterWorks (J. Woodworth), "Arrester Failure Root Cause Analysis", dated 4/3/14

- McQuinn Electrical Power Consulting (N. McQuinn) report, dated 3/16/14
- Exponent Failure Analysis (I. Kerszenbaum), "DCPP Phase B and C Lightning Arrester Inspection at ABB" dated 2/13/14
- EACH Engineering (E. Cherney), "Flashover of Unit 2 "A" Phase Silicone Rubber 500-KV CCVT Manufactured by Trench", dated 2/27/13
- Arizona State University (R. Gorur), "Evaluating Housing Materials from CCVT and Surge Arrester at DCPP", dated February 2013

Diablo Canyon Power Plant Licensee Event Reports

- DCPP Unit 1 LER 2007-001-00, dated July 11, 2007
- DCPP Unit 2 LER 2008-001-00, dated October 15, 2008
- DCPP Unit 2 LER 2012-002-00, dated December 10, 2012
- DCPP Unit 2 LER 2012-002-01, dated June 26, 2013
- DCPP Unit 2 LER 2013-5-0, dated September 5, 2013
- DCPP Unit 2 LER 2012-5-1, dated November 21, 2013
- DCPP Unit 2 LER 2014-001-00, dated April 3, 2014

The following additional Non-DCPP documentation was reviewed by MPR during this effort:

- Over 40 technical papers published by professional groups, scientists, or academics that concerned the design, development, or testing of polymer insulators were obtained and utilized, some of which are cited in Appendix A.

ATTACHMENT 8

PG&E Data Request Response ORA_039-Q01

and selected attachments

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_039-Q01		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_039-Q01		
Request Date:	August 9, 2016	Requester DR No.:	039
Date Sent:	August 23, 2016	Requesting Party:	Office of Ratepayer Advocates
PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY, CHAPTER 1, TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION

QUESTION 1

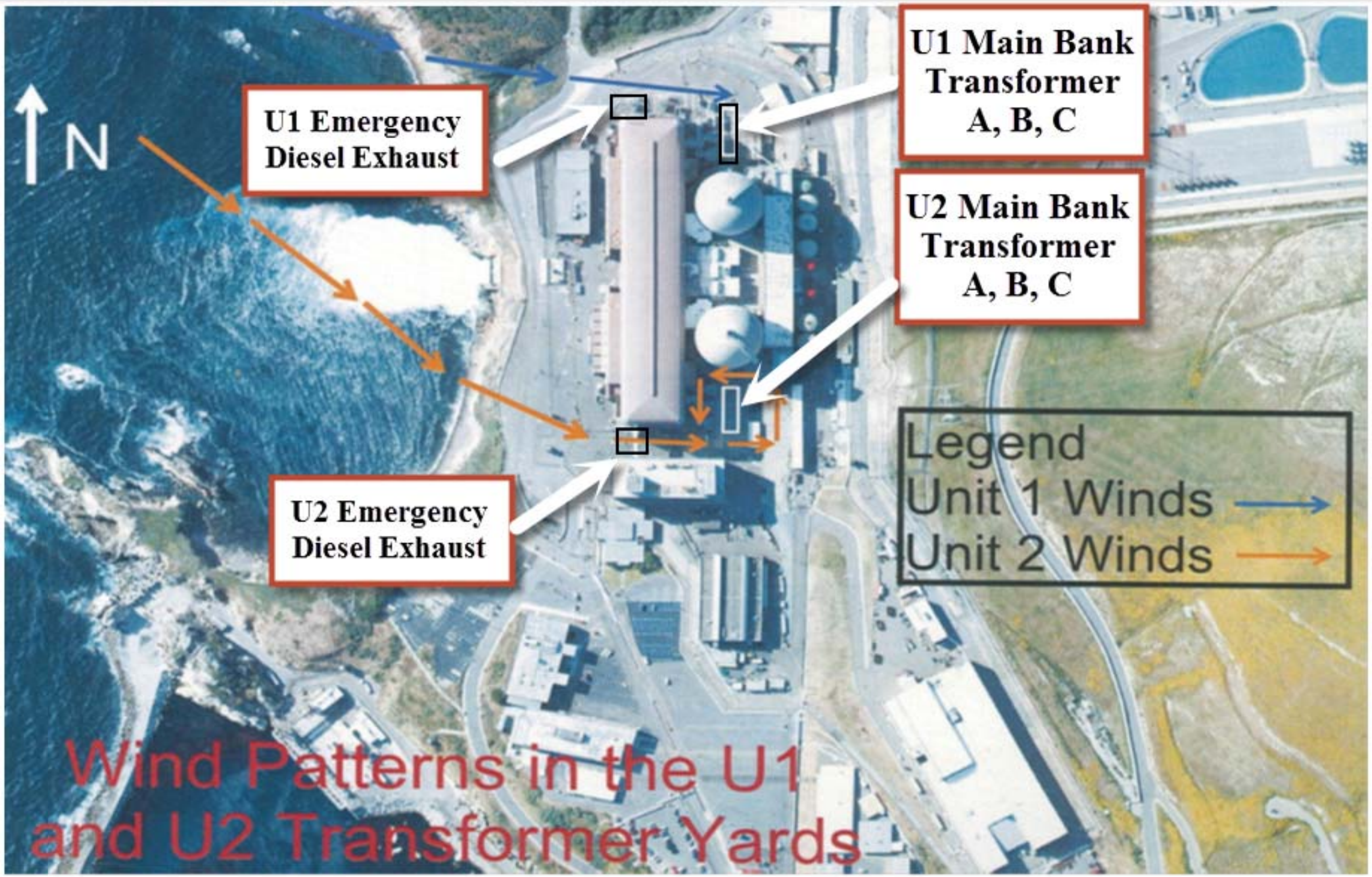
In response to Data Request #37 Question 1, PG&E provided a map of DCPP lightning arrester locations. However, the image was too expansive to show specific equipment. Please provide a detailed map/diagram of DCPP that labels each of the following Unit 1 and Unit 2 equipment:

a. A, B and C phase Main Bank Transformers
b. A, B and C phase lightning arresters
c. A, B and C phase dead end insulators
d. Emergency Diesel Generator exhaust stack with an arrow indicating the direction exhaust blows

ANSWER 1

a) Please refer to ERRA-2013-PGE-Compliance_DR_ORA_039-Q01-attch_1.pdf. And attachments ERRA-2013-PGE-Compliance_DR_ORA_039-Q01-attch_5 and 6 for plan view diagrams on transformer layout in each unit.
b) Please refer to ERRA-2013-PGE-Compliance_DR_ORA_039-Q01-attch_2.pdf and ERRA-2013-PGE-Compliance_DR_ORA_039-Q01-attch_3.pdf.
c) Please refer to ERRA-2013-PGE-Compliance_DR_ORA_039-Q01-attch_4.pdf.
d) The Unit 2 diesel generator exhaust stacks discharge through the south Turbine Building wall at approximately 106' elevation and the Unit 1 diesel generator exhaust stacks discharge through the turbine building roof at approximately 218' elevation and the approximate location is depicted in attachment ERRA-2013-PGE-Compliance_DR_ORA_039-Q01-attch_1.pdf.

Main Bank Transformer and Diesel Exhaust Locations



Lightning Arrestors

Dead End Insulators

ATTACHMENT 9

PG&E Data Request Response ORA_039-Q02

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_039-Q02		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_039-Q02		
Request Date:	August 9, 2016	Requester DR No.:	039
Date Sent:	August 23, 2016	Requesting Party:	Office of Ratepayer Advocates
PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY, CHAPTER 1, TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION

QUESTION 2

In Data Request #37 Question 9, ORA asked the following questions and PG&E made the following responses.

> 9b: Since the catastrophic failure was an issue of the porcelain HV Bushing and not the lightning arresters, why did PG&E decide to switch the lightning arrester materials from porcelain to polymer as well? Please provide any supporting documents on this decision.
>
> PG&E: "The nature of the catastrophic failure of the HV bushing and collateral damage caused by the failure caused DCPP to reconsider the porcelain material. Removal of the porcelain was a personal safety consideration. This is documented in the Corrective actions to RCE 50518473 U2"A" Phase CCVT Flashover Results in U2 trip document."
>
> 9c: Since PG&E switched back to porcelain lightning arresters as a corrective action following the 2014 outage, please explain why the underlying reasons for the switch from porcelain to polymer lightning arresters are no longer a concern.
>
> PG&E: "Personal safety continues to be a focus. In addition DCPP and PG&E consider Industrial Safety and Nuclear Safety in the considerations for equipment replacement. Industrial safety relates to process is to protect and promote the health and safety of employees and others who work in and about nuclear generation facilities, primarily through control of the working environment. Nuclear Safety relates to protecting the health and safety of the public. More specifically regarding lightning arresters this safety measure encompasses equipment reliability and being able to perform its function when required. The switch from the polymer type arrester to the porcelain type arrester included these considerations. Additionally in discussing the performance with the consultants DCPP retained they provided the reference to IEEE/ANSI C62.11 standard for lightning arrester certification. DCPP learned that Lightning Arresters do not fail the same as a High voltage bushing."

a. As a result of RCE 50518473 U2"A" Phase CCVT Flashover Results in U2, PG&E switched the lightning arrester material from porcelain to polymer due to personal safety considerations.

   i. At that time, what were the “personal safety considerations” of using porcelain versus polymer lightning arresters?

   ii. Was one of the concerns the possibility that the porcelain lightning arresters would fail in the same manner as the porcelain high voltage bushing?

b. When did DCPP learn that “lightning arresters do not fail the same as a high voltage bushing”? (Date if available) Please provide documentation showing when PG&E learned this information.

c. What is the “IEEE/ANSI C62.11 standard for lightning arrester certification”? Please provide the document with this standard.

d. Does this standard show that lightning arresters do not fail the same as a high voltage bushing? If so, how? If not, please explain the relevance of the reference in PG&E’s response.

e. When PG&E decided to change the lightning arresters from polymer back to porcelain, what were the concerns?

   i. Were safety concerns one of the issues?

   ii. What were the reasons that PG&E determined that porcelain lighting arresters would be safe relative to polymer lightning arresters?

   iii. Was one of the reasons that PG&E determined that porcelain lightning arresters would be safe relative to polymer lightning arresters the fact that PG&E learned that lightning arresters don’t fail the same way as the high voltage bushing did in the RCE 50518473 U2"A" Phase CCVT Flashover?

ANSWER 2

a.

   i. Porcelain was used as an insulation material on the HV bushings and the lightning arresters. This material is hard, brittle and dense which allows it to become a damaging projectile if expelled during a failure. The polymer insulation material is a soft rubber compound and cannot fracture like porcelain or become a damaging projectile during a failure. Due the increased personnel safety benefits of the polymer insulation material, PG&E decided to change the high voltage components utilizing porcelain insulation inside the Unit 1 and Unit 2 transformer yards to components that utilized polymer insulation material. This was discussed in attached 2011 Plant Health Issue Plan (refer to attachment ERRA-2013-PGE-Compliance_DR_ORA_039-Q02 attch_1), that initiated the lightning arrester replacement. The primary concern was that the porcelain material would be ejected at sufficient velocity during a failure to pose a personnel safety threat.

   ii. Yes.

b. DCPP learned that lightning arresters have a much lower probability of failure similar to the high voltage bushing in July 2014 through the attached Jonathan

Woodworth - Arresterworks report "Porcelain Housed Arrester Rupture Probability Assessment at DCPP". Refer to ERRA-2013-PGE-Compliance_DR_ORA_39-Q03-attch_2.

c. IEEE/ANSI C62.11 is the "Standard for Metal-Oxide Surge Arresters for AC power Circuits (>1 kV)". This standard outlines the testing and performance requirements required to "Demonstrate that an arrester is able to survive the rigors of reasonable environmental conditions and system phenomena while protecting equipment and/or the system from damaging overvoltages caused by lightning, switching, and other undesirable surges." This document is for sale by IEEE; copyright and licensing limitations prevent this document from being distributed in this response.

d. The standard requires that lightning arresters do not fail during the testing certification. An arrester that catastrophically ruptures during certification testing would fail to satisfy the certification requirements.

e.

   i. Yes, safety was a concern. This change would have not been made without the support of the Jonathan Woodworth-Arresterworks report concluding that there is a low probability that a porcelain lightning arrester used to protect the 500kV transformers at DCPP would violently rupture and jeopardize personnel safety.

   ii. PG&E determined that porcelain lighting arresters would be safe due to a low probability of violently rupturing. This determination is due to the low probability of lightning arrester failure combined with the use of venting ports that limit the lightning arrester internal pressure to prevent a lightning arrester rupture if a failure were to occur. This conclusion was supported by the Woodworth-Arresterworks report and IEEE IEEE/ANSI C62.11 certification testing requirements.

   iii. PG&E learned that porcelain lightning arresters have a low probability of failure similar to the high voltage bushings during the RCE 50607838 U2 "B" Phase CCVT flashover.

ATTACHMENT 10

PG&E Data Request Response ORA_039-Q03

PACIFIC GAS AND ELECTRIC COMPANY
Energy Resource Recovery Account 2013 – Compliance
Application 14-02-008
Data Response

PG&E Data Request No.:	ORA_039-Q03		
PG&E File Name:	ERRA-2013-PGE-Compliance_DR_ORA_039-Q03		
Request Date:	August 9, 2016	Requester DR No.:	039
Date Sent:	August 23, 2016	Requesting Party:	Office of Ratepayer Advocates
PG&E Witness:	Cary Harbor	Requester:	Xian Ming Li

RE: PG&E TESTIMONY, CHAPTER 1, TESTIMONY REGARDING REVISED ROOT CAUSE EVALUATION

QUESTION 3

In Data Request #37 Question 5, ORA asked the following question and PG&E made the following response.

> Question 5. On page 112 of Attachment A, in RCE A, ABB states "No signs of manufacturing defects were observed." Given this information, please explain how the probable cause of assembly errors on page 4 of Attachment A can be applicable to the A Phase lightning arrester.
>
> PG&E: "This information came from ABB's original report (ABB RMA 804) from the original RCE 50573100. During the second event RCE 50607838 investigation the technical analysis is contained in attachments; 1) Draft Isidor Kerzenbaum Arrester Investigation, 2) Nigel McQuin Serge Arrester Investigation Report, 3) Jonathan Woodworth Surge Arrester Investigation Report. Note: These attachments are part of RCE 50607838 rev 3. ABB RMA 829 report on page 7 alludes to the 'a slight assembly nonconformance was found in the positioning of the MOV blocks within the stack assembly.'"

The quote from the ABB RMA 829 report is part of RCE B and refers to Unit 2 LAs inspected by ABB in February 2014.

a. Is the finding from the ABB report in RCE B the reason that the Revised RCE reports the following probable cause of an internal failure of the LA: "Assembly errors resulting in internal contamination initiating an internal failure"?

b. If so, please explain why this probable cause is applicable to the Revised RCE when the ABB RMA 829 report does not state that the Unit 2 A Phase LA that failed in 2013 had an assembly nonconformance.

c. If not, please provide any evidence showing that the Unit 2 A Phase LA that failed in 2013 had an assembly error.

ANSWER 3

a. Yes.

b. The probable cause from the Unit 2 B Phase LA RCE was incorrectly applied to the revised Unit 2 A Phase LA RCE.

c. Because the probable cause was incorrectly applied, this response is not applicable.