Electric System Fragility
SERA - ShakeMap

February 4 2022

John Eidinger

Agenda

- Engineers who ask Lots of Questions
- Anchorage 2018 Electric System Damage
- Empirical Data - 72 earthquakes
- Test Data - Modern
- Distribution Systems - the $300 Billion Elephant in the room no one talks about
- Questions and Comments

Key Points

- Substations: We have "nearly solved" the seismic vulnerability. Some utilities are well on their way to implementation. Some utilities are like Dinosaurs.
- Distribution Systems: The Elephant on the room
- How much to complete the job? Brute force = $300,000,000,000 for California.
- SERA and ShakeMaps: tools to quantify, evaluate, and make smart decisions. Maybe find a $40 B mitigation plan that does 95% of the $300 B brute force plan.

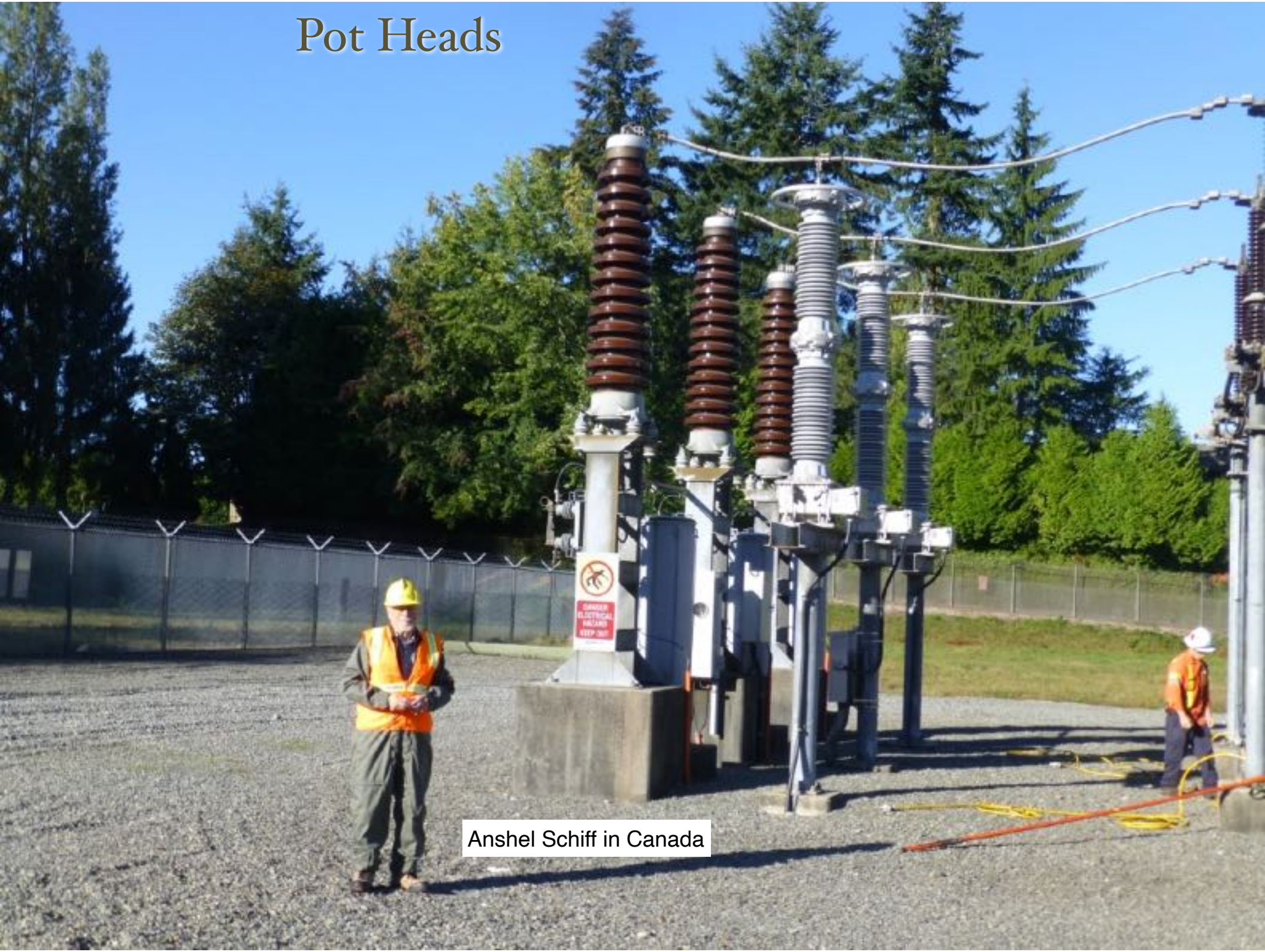

Anshel Schiff
Alex Tang

Anshel Schiff in Buffalo

Communication Battery

Anshel Schiff in Oregon

Pot Heads



Anshel Schiff in Canada

John MacKenzie, Transpower + Orion's seismic designer engineer

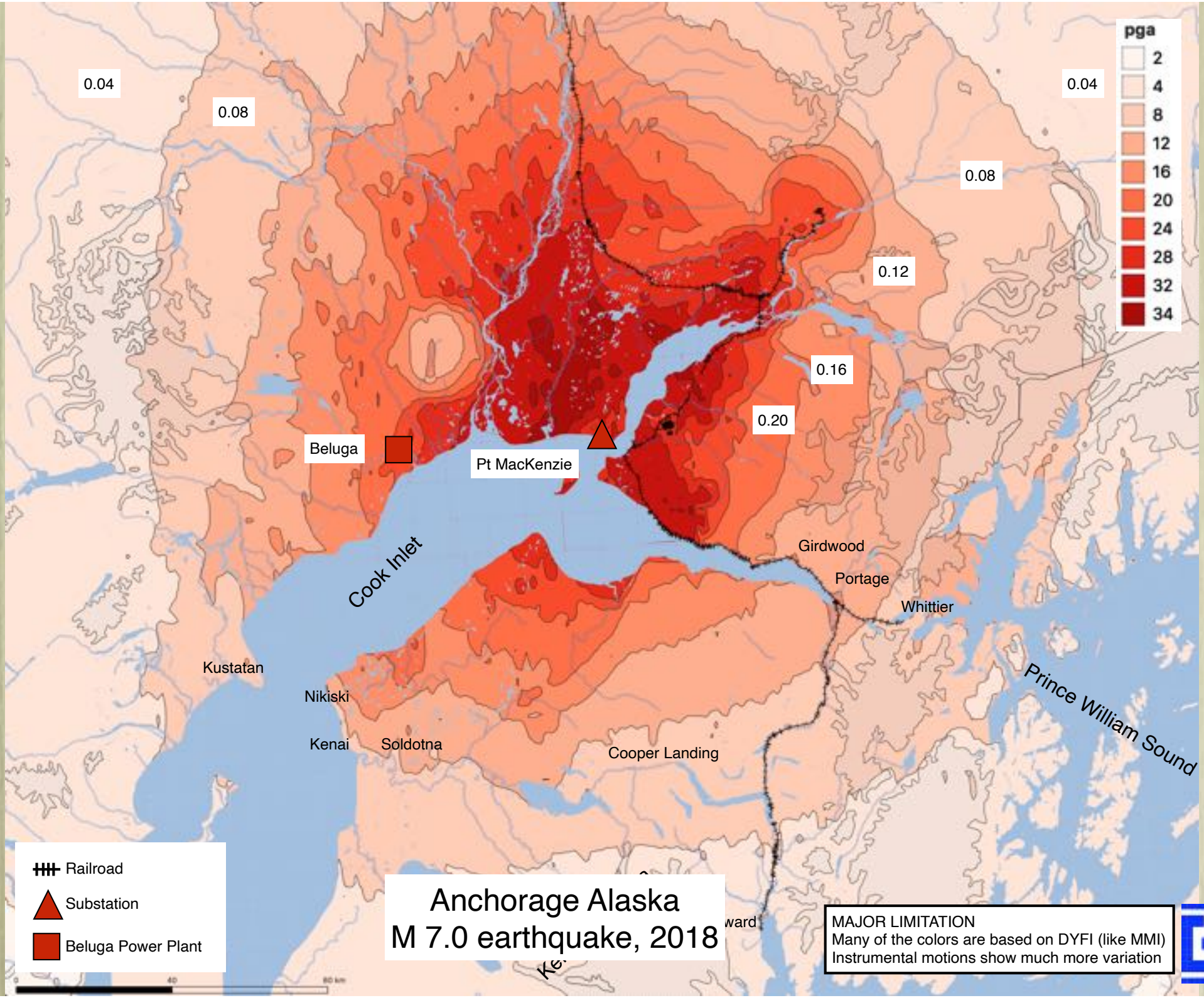
John and John in New Zealand

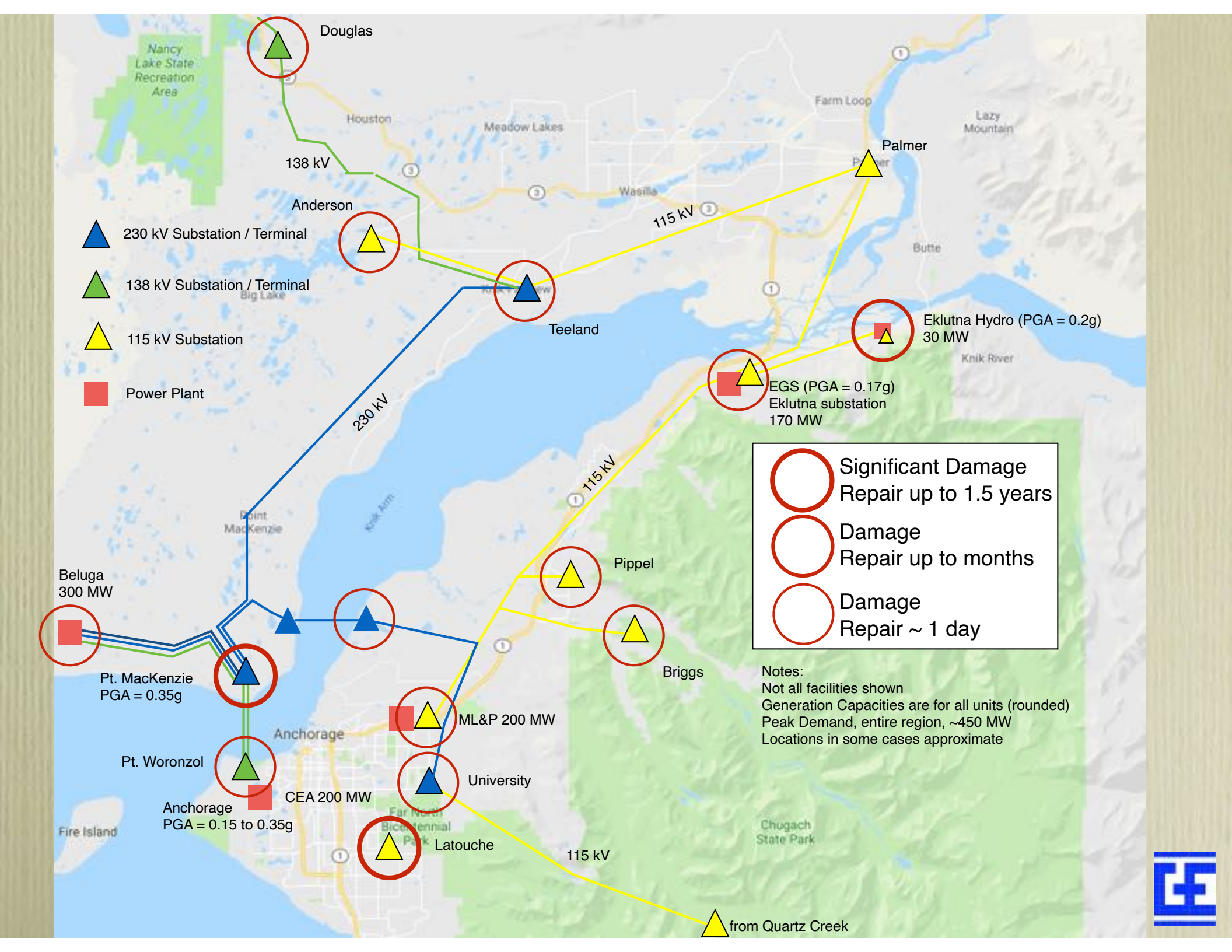
Will Liquefaction Damage a 230 kV Rigid Bus Substation at PGA = 0.5g?

Large sand boil in 220 kV Yard


What about the millions of small stuff?
50
14.4
50
14.4
50
14.4
50
14.4


When we see this..... With a little coordination,
2 months later we are going to test!


pga
2
4
8
12
16
20
24
28
32
34
0.04
0.08
0.04
0.08
0.12
0.16
0.20
Beluga
Pt MacKenzie
Cook Inlet
Girdwood
Portage
Whittier
Prince William Sound
Kustatan
Nikiski
Kenai
Soldotna
Cooper Landing
Railroad
Substation
Beluga Power Plant
Anchorage Alaska
M 7.0 earthquake, 2018
MAJOR LIMITATION
Many of the colors are based on DYFI (like MMI)
Instrumental motions show much more variation

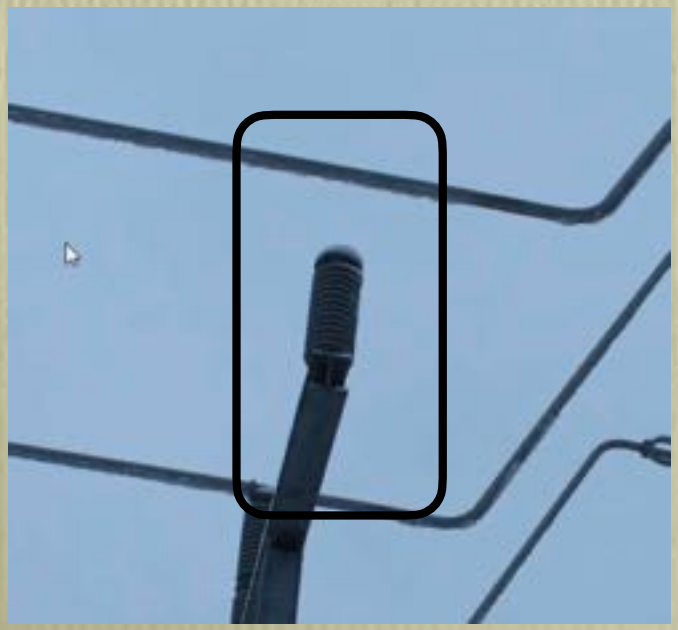

Douglas
Nancy Lake State Recreation Area
Houston
Meadow Lakes
Farm Loop
Lazy Mountain
Palmer
138 kV
Anderson
Wasilla
115 kV
230 kV Substation / Terminal
138 kV Substation / Terminal
115 kV Substation
Power Plant
Big Lake
Teeland
Butte
Eklutna Hydro (PGA = 0.2g)
30 MW
Knik River
EGS (PGA = 0.17g)
Eklutna substation
170 MW
230 kV
115 kV
Significant Damage
Repair up to 1.5 years
Damage
Repair up to months
Damage
Repair ~ 1 day
Point MacKenzie
Knik Arm
Pippel
Beluga
300 MW
Briggs
Pt. MacKenzie
PGA = 0.35g
ML&P 200 MW
Anchorage
Pt. Woronzol
University
CEA 200 MW
Anchorage
PGA = 0.15 to 0.35g
Fire Island
Latouche
115 kV
Chugach State Park
from Quartz Creek
Notes:
Not all facilities shown
Generation Capacities are for all units (rounded)
Peak Demand, entire region, ~450 MW
Locations in some cases approximate

MEA Briggs Substation

Rigid Bus. Surge Arrestors. Transformer slid, breaking 2 bushings.+ 2 SAs.
PGA ~ 0.30g

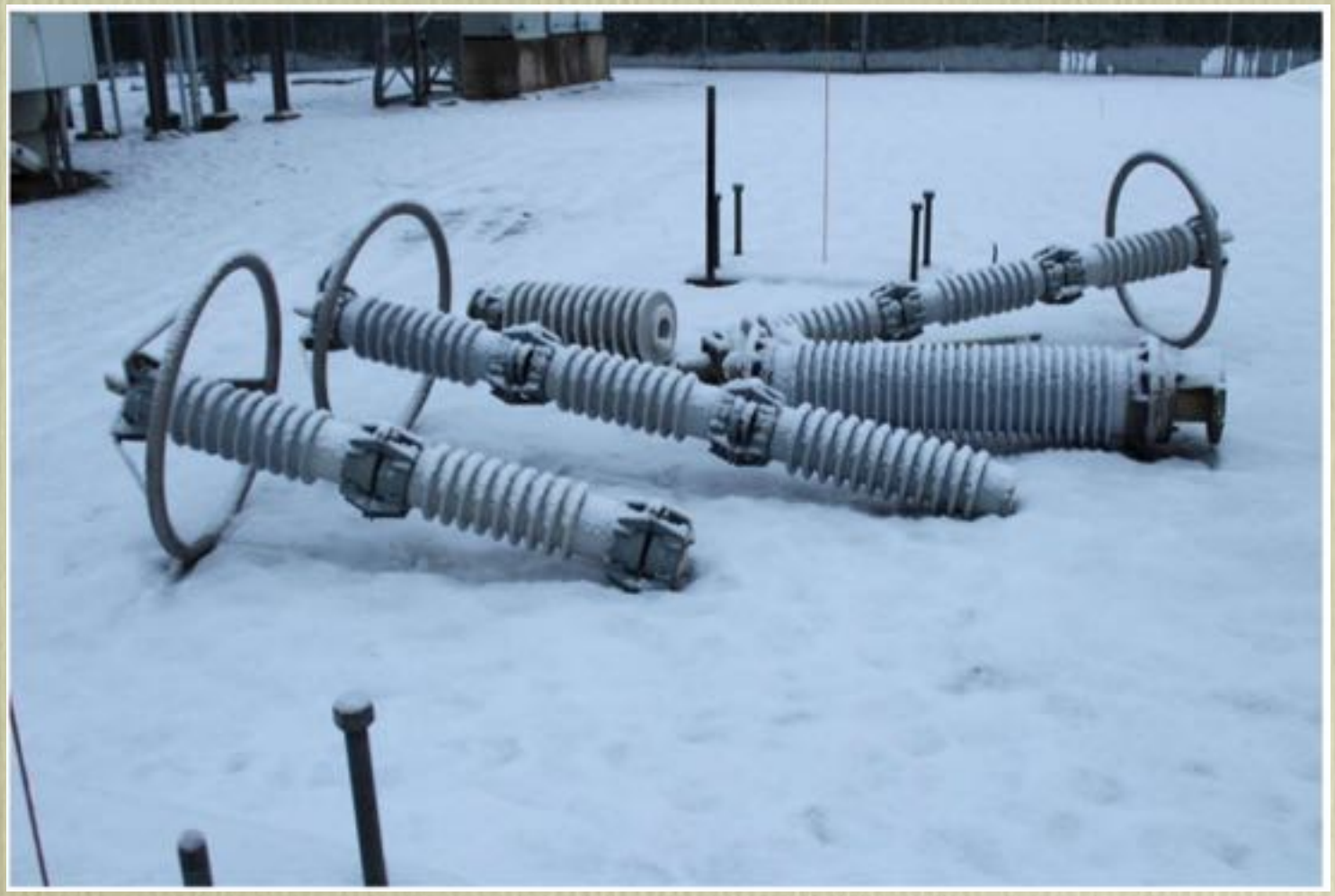
MEA Douglas Substation

Rigid Bus Expansion Joints, Bus Supports. PGA ~ 0.30g



Excessive differential movements leads to failures
Switch streel structures and bus supports
use I-beams, low frequencies,
twisting / torsion. All this is readily computed.
Suitable connectors are available.
Do utilities (and their A/Es) turn a blind eye?
Sunshine will expose the weaknesses.
CEA, ML&P and MEA all have work to do.

MEA Anderson Substation



Surge Arrestors. Circuit Switchers (candlestick breakers)
PGA ~ 0.30g

MEA Pippel Substation

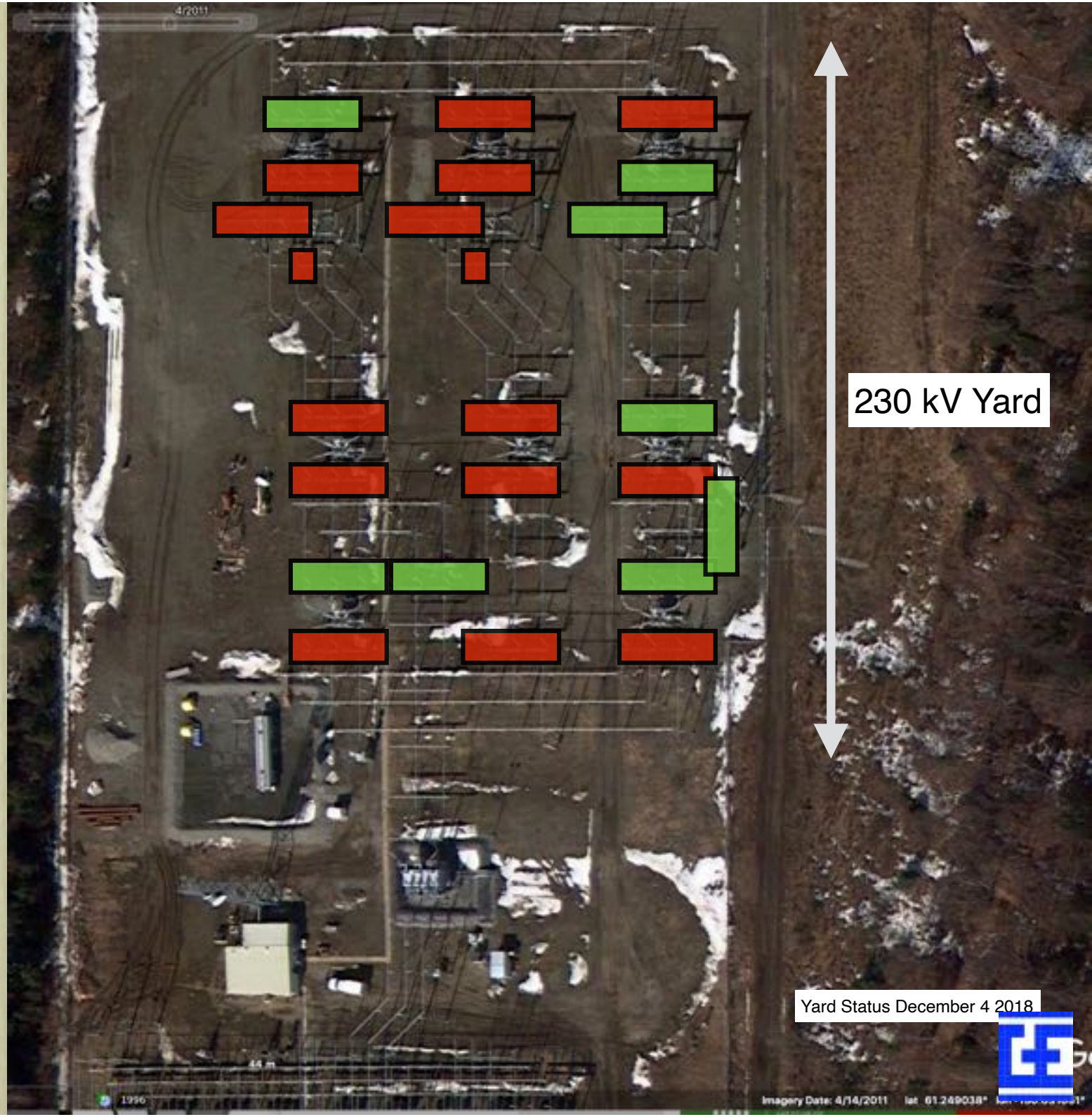
Candlestick Breaker. Surge Arrestors. Bus. 115 kV DS + CB. PGA ~ 0.30g

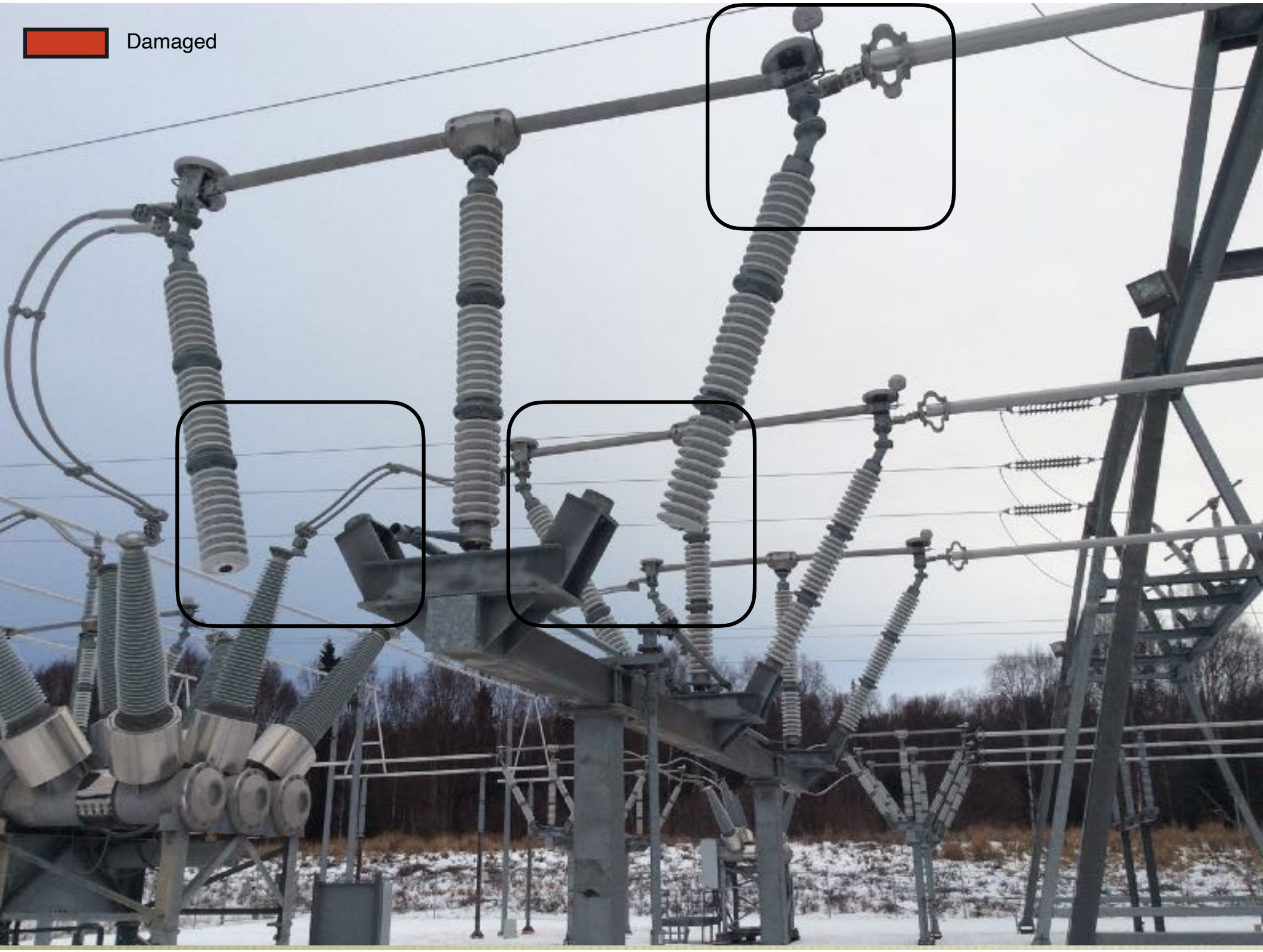
Damaged

Undamaged

CEA
Pt MacKenzie 2018
230 138 kV
Lat 61.2496
Long -150.0268

North




Damaged

Key Findings

- Modern Seismic-Qualified Substations: a WHOLE LOT BETTER than what was orginally built in the 1960s and 1970s
- Old, vulnerable equipment had Fragility levels PGA = 0.2g to 0.5g
- New, qualified equipment has Fragility levels commonly PGA = 1.3g+

Why do we still have power outages?

- There remain (relatively minor) weaknesses at substations (mostly related to the bus)
- HUGE: the low voltage distribution system
  - Buried Cables: ~450 failures in 2010/2011
  - Overhead: ~1,000 failures in M 7; 50 failures in M 6.
  - What will a M 8 (San Andreas) produce: 5,000 failures? Or a Compton M 7 thrust event?

Consider the Issues

- Low Voltage: commonly 16-32 manhours per repair
- 50 repairs * 16 manhours = 800 manhours.
    - Apply 50 repair people @ 12 hours / day, you are done in 32 hours. People are “happy”
- 5,000 repairs * 20 manhours = 100,000 manhours.
    - Apply 1,000 repair people @ 12 hours / day, you are done in 8.33 days (200 hours). People are “not happy”

What should Utilities do?

- Continue procurement of IEEE 693 qualified equipment. ✓ ✓ ✓ ✓ ✓ ✓
- Implement better cable flex bus and rigid bus detailing. ✓ ✓ ✓ ✓ ✓ ✓
- Bury low voltage feeders ($300 Billion for California). CEO Patricia Pope recently announced the first $20 Billion for PG&E. 90% improvement
- Emergency plans to use 10,000 repair people. COST EFFECTIVE
- Seismic design for low voltage overheads (insulated cables, no drop spans, torsion design for elevated multi-transformers, deeper embendment in liquefaction zones). CPUC / Boards to allow this to be recovered in rates.
- "Smart" de-energization? Can reduce about 20% of overhead repairs. Unthinkable 30 years ago. Technically feasible today. Can a Utility depend on third parties? A $10,000,000 grant from Congress's latest $1.1 T Infrastructure plan might kick start a demonstration project - Who will step up to the plate? An investor-owned utility? A public-owned utility?

Where to get Reports

- http://www.geEngineeringSystems.com
- All free - see copyright, creative commons deed on the web site
- Books (typ. 300 pages) that describe seismic fragility models for:
  - Natural Gas Pipes
  - Water Pipes (Tanks, Levees,Tunnels)
  - Electric Utility Components (new multi-volume report late 2022)
  - Non Structural Components
  - Fire Following Earthquake
- New TCLEE Reports No. 1 through 7 (earthquakes 2014 through 2021)

What is SERA?

- **S**ystem **E**arthquake **R**isk **A**nalysis
- 32 years of development
- Available by license to Utilities

SERA and ShakeMap

- **SERA** allows several kinds of earthquakes: User-defined Scenario, USGS Probabilistic, ShakeMap, User-defined Probabilistic
- After most earthquakes M > 5, run SERA within a few minutes post-earthquake. If SERA predicts power outages or damage, engineers will go out to inspect and verify.
- Current Interface: ShakeMap grid.xyz or grid.xml file.
- Better interface: Stationlist.txt (the raw data)

Good, Bad, (and the Ugly)

- **GOOD.** grid.xyz files are “free”. Gives a quick look at what the range of damage / power outages might be.
- **BAD.** grid.xyz Initial release files (< 1 hour) are unreliable. Beta is not 0.5±. It can be >> 0.5. Revised files might take 5+ years to create. Improper data may exist for a long time (eg. Carquinez instruments that measured bridge pounding with PGA ~ 1.0g are still embedded in the Napa 2014 ShakeMaps)
- **Fine points**. Mish mash of DYFI and instrumental values gives artificial smoothing. MMI is NOT the way to go if you want better loss estimates.
- A “**smarter**” Shakemap would use the instrumental data (from USGS) and utility-specific Vs30, GMPE, basin, liquefaction, landslide, surface faulting info.
- “**Standardized**” Shakemap files. Drudgery of writing / updating parsers and exception handling for shifting .xyz, .xml, .json, .txt, .shp file formats. PLEASE Include 'legacy" file formats even if new ones are added.

ShakeMap SERA Merge?

- SERA 2030 vision: maintenance by the utilities.
- David Wald and crew are plenty darn smart.
- Can the US Federal Government maintain the electric grid infrastructure?

SERA MODELS - LARGE ELECTRIC

BC Hydro. 483 substations

BPA. 521 substations

PG&E. 981 substations

SCE. 1247 substations

SDG&E. 58 substations

PacifiCorp. 1400 substations

Total.
About 5,000 substations
350,000 transmission towers
11 million wood poles
60 million people

Epicenters of
Historical Earthquakes

PG&E Service Area

72 Earthquakes
1980 - 2020, M ≥ 4.5

plus...

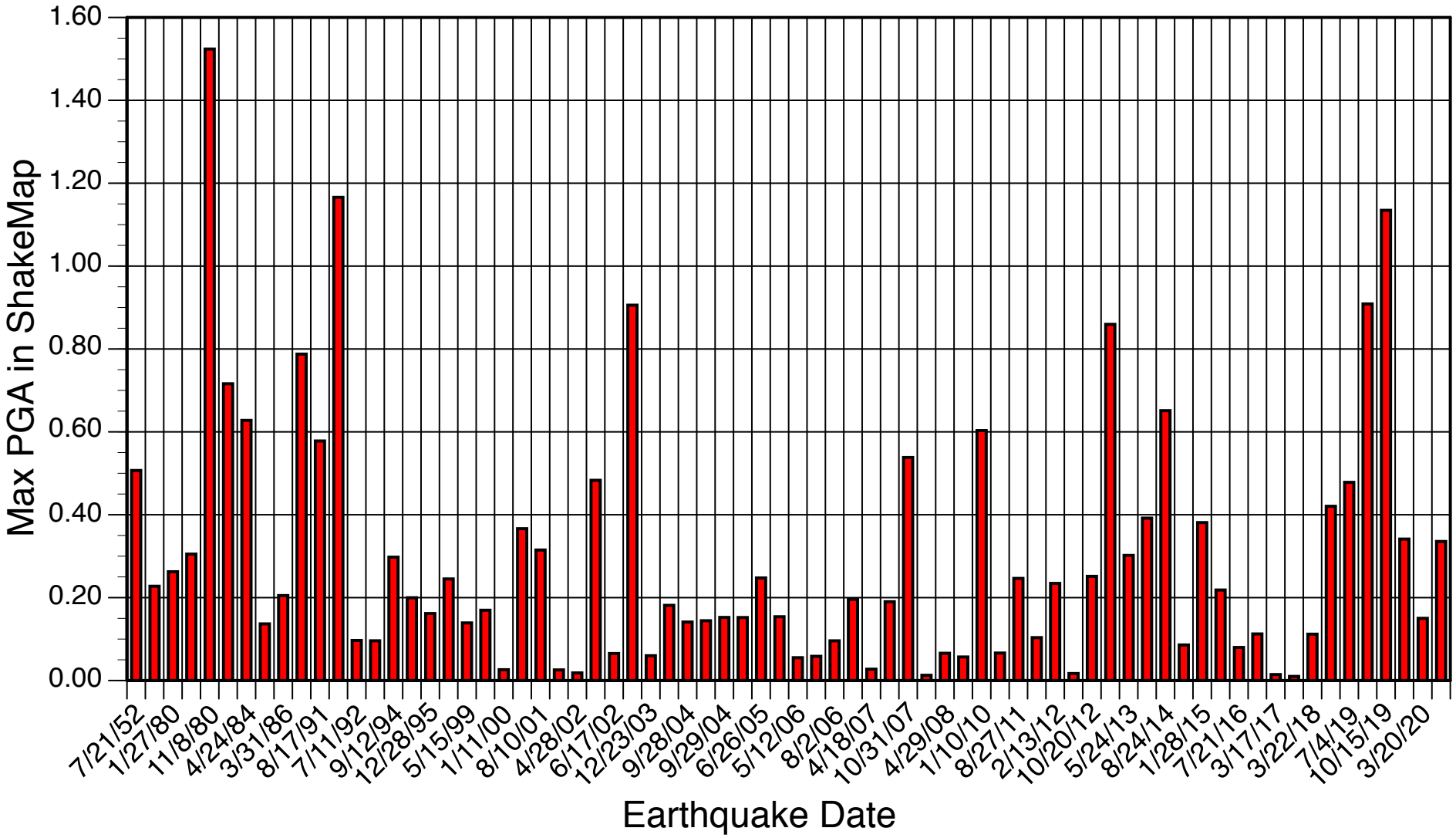
$20 Billion after M 6.0 2021

EQ	Name	M	Event Date	Max PGA, g	EventID
72	White Wolf	7.2	07/21/1952	0.5068	Whitewolf
29	Greenville	5.8	01/24/1980	0.2275	19800124190009
30	Greenville	5.4	01/27/1980	0.2625	19800127023336
10	Central CA	6.1	05/25/1980	0.3050	19800525163347
33	Humboldt Offshore	7.2	11/08/1980	1.5237	19801108000000
61	Coalinga	6.3	05/02/1983	0.7161	19830502234237
39	Morgan Hill	6.2	04/24/1984	0.6277	19840424211520
62	Ridgemark	5.4	01/26/1986	0.1367	19860126192051
63	Calaveras	5.6	03/31/1986	0.2050	19860331115540
35	Loma Prieta	6.9	10/19/1989	0.7876	19891019000000
31	Honeydew	6.1	08/17/1991	0.5780	19910817192940
43	Cape Mendocino	7.2	04/25/1992	1.1658	269151
6	California City	5.3	07/11/1992	0.0967	19920711181416
24	Gilroy	4.9	01/16/1993	0.0959	19930116062934
21	Gardnerville	5.7	09/12/1994	0.2976	19940912122343
32	Humboldt	5.5	12/26/1994	0.1997	19941226141029
51	Smith Valley	5.5	12/28/1995	0.1617	19951228182759
48	Salinas	5.2	08/12/1998	0.2451	19980812141026
36	Mammoth Lakes	5.5	05/15/1999	0.1390	19990515132210
5	Bolinas	4.6	08/17/1999	0.1696	21044694
12	Cloverdale	4.6	01/11/2000	0.0261	21076750
60	Yountville	5.0	09/03/2000	0.3664	20000903083630
3	Blairden	5.2	08/10/2001	0.3149	21188442
46	Pinnacles	4.6	12/28/2001	0.0256	21207275
20	Ferndale	4.6	04/28/2002	0.0183	21223451
26	Gilroy	4.9	05/13/2002	0.4831	21254601
2	Bayview	5.2	06/17/2002	0.0652	21231051
50	San Simeon	6.5	12/22/2003	0.9057	20031222191558
7	Cambria	4.7	12/23/2003	0.0598	21324051
13	Cobb	4.6	02/18/2004	0.1814	21344222
11	Cholame	4.7	09/28/2004	0.1411	21400461
4	Bodfish	5.0	09/29/2004	0.1443	14095628
41	Parkfield	5.0	09/29/2004	0.1522	21401069
38	Maricopa	4.6	04/16/2005	0.1520	14138080
53	Tahoe Vista	4.8	06/26/2005	0.2474	21465580

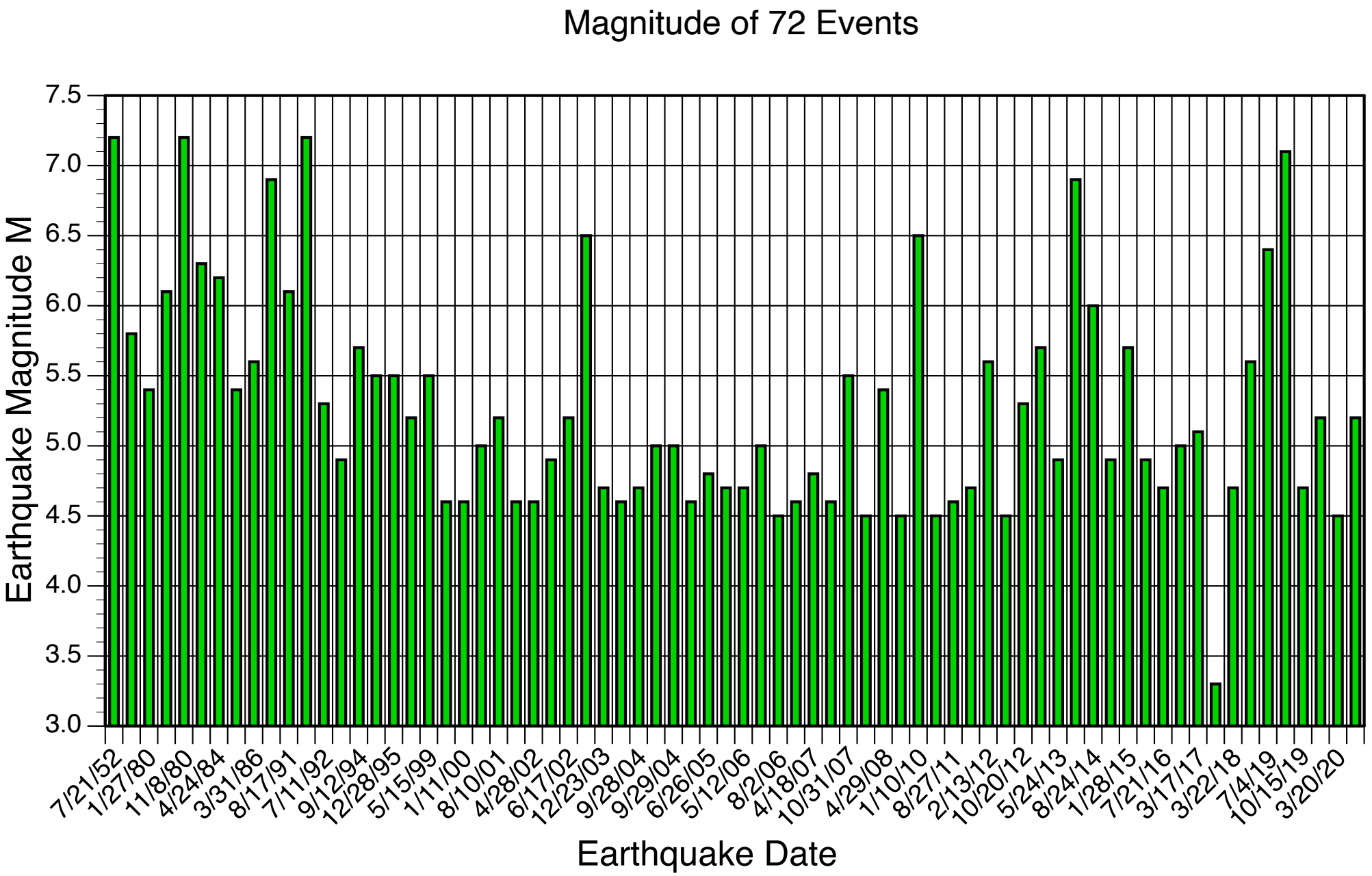
EQ	Name	M	Event Date	Max PGA, g	EventID
28	Grapevine	4.7	09/22/2005	0.1539	14186612
22	Geysers	4.7	05/12/2006	0.0551	21516950
44	Petrolia	5.0	07/19/2006	0.0584	21527987
27	Glen Ellen	4.5	08/02/2006	0.0958	21530368
14	Cobb	4.6	10/20/2006	0.1959	21543835
34	Lake Pillsbury	4.8	04/18/2007	0.0273	40195779
37	Mammoth Lakes	4.6	06/12/2007	0.1901	51182810
15	Alum Rock East Foothills	5.5	10/31/2007	0.1644	40204628
47	Rancho Tehama	4.5	01/19/2008	0.0126	51194914
59	Willow Creek	5.4	04/29/2008	0.0658	40216664
16	East Quincy	4.5	12/16/2008	0.0568	51213957
18	Eureka Offshore	6.5	01/10/2010	0.6031	71338066
49	San Juan Batista	4.5	01/12/2011	0.0663	71508850
45	Pinnacles	4.6	08/27/2011	0.2464	71627835
58	Whitehawk	4.7	10/26/2011	0.1035	71671056
57	Weitchpec	5.6	02/13/2012	0.2343	71734741
54	Talmage	4.5	09/25/2012	0.0169	71847715
40	New Idria	5.3	10/20/2012	0.2514	71863625
8	Susanville Canyon Dam	5.7	05/23/2013	0.8594	71996906
9	Canyon Dam	4.9	05/24/2013	0.3019	71997821
17	Eureka	6.9	03/10/2014	0.3919	72182046
52	South Napa	6.0	08/24/2014	0.6512	72282711
42	Parkfield	4.9	09/30/2014	0.0858	21401170
19	Ferndale	5.7	01/28/2015	0.3811	72387946
56	Wasco	4.9	02/24/2016	0.2184	37528064
1	Bayside	4.7	07/21/2016	0.0798	72664436
23	Geysers	5.0	12/14/2016	0.1124	72737985
55	Upper Lake	5.1	03/17/2017	0.0144	72672610
25	Gilroy	3.3	03/06/2018	0.0099	72979736
70	Petrolia	4.7	03/22/2018	0.1118	72988926
71	Petrolia	5.6	06/22/2019	0.4204	73201181
64	Ridgecrest	6.4	07/04/2019	0.4782	38443183
65	Ridgecrest	7.1	07/06/2019	0.9087	38457511
66	Tres Pinos	4.7	10/15/2019	1.1346	73292360
69	Petrolia	5.2	03/18/2020	0.3413	73355700
68	Johnson Lane	4.5	03/20/2020	0.1500	00719663
67	Bodie	5.2	04/11/2020	0.3355	73367270

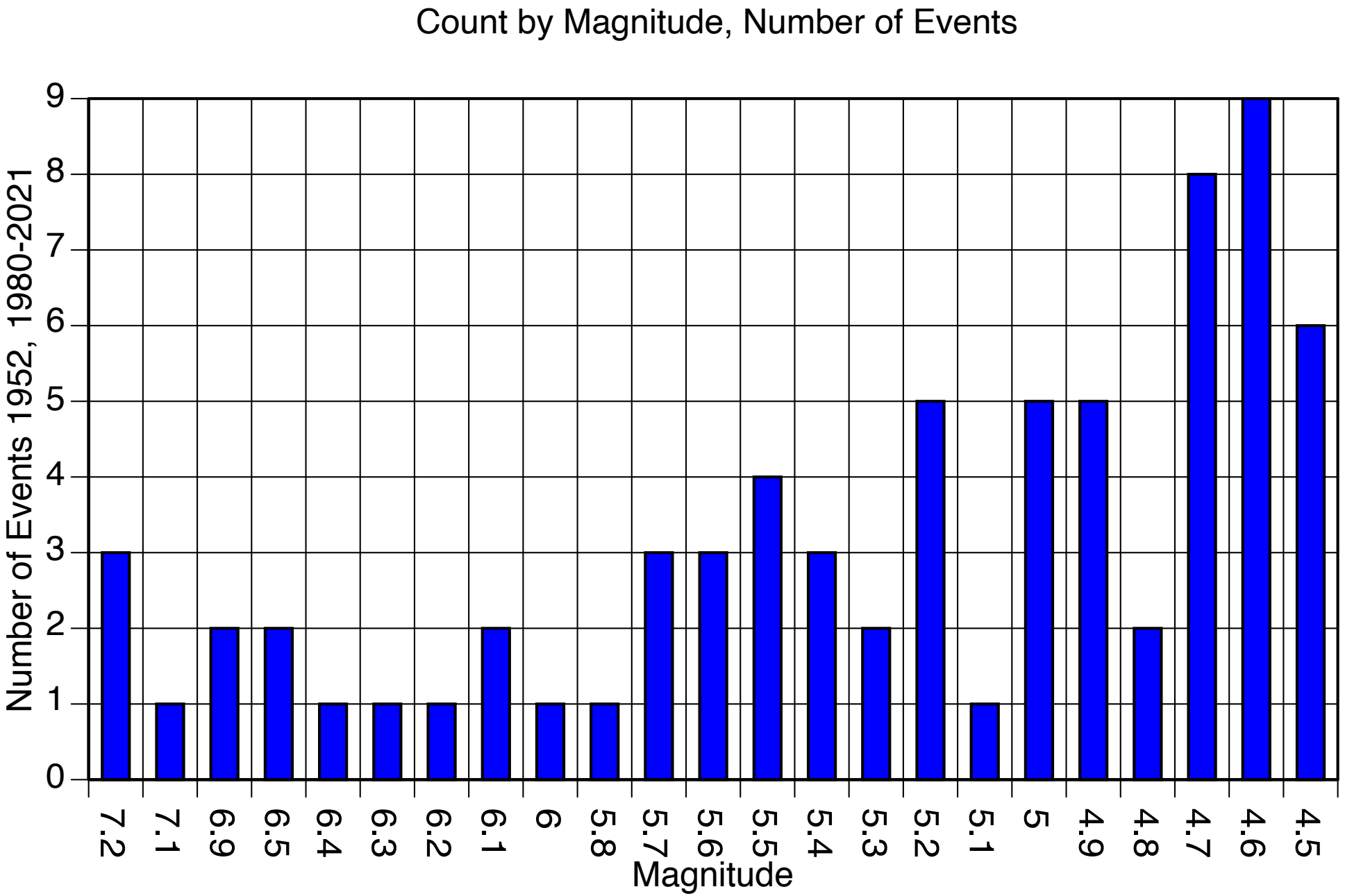
Historical Earthquakes: PG&E Service Area: 1952 - 2020

Maximum Horizontal PGA (g)

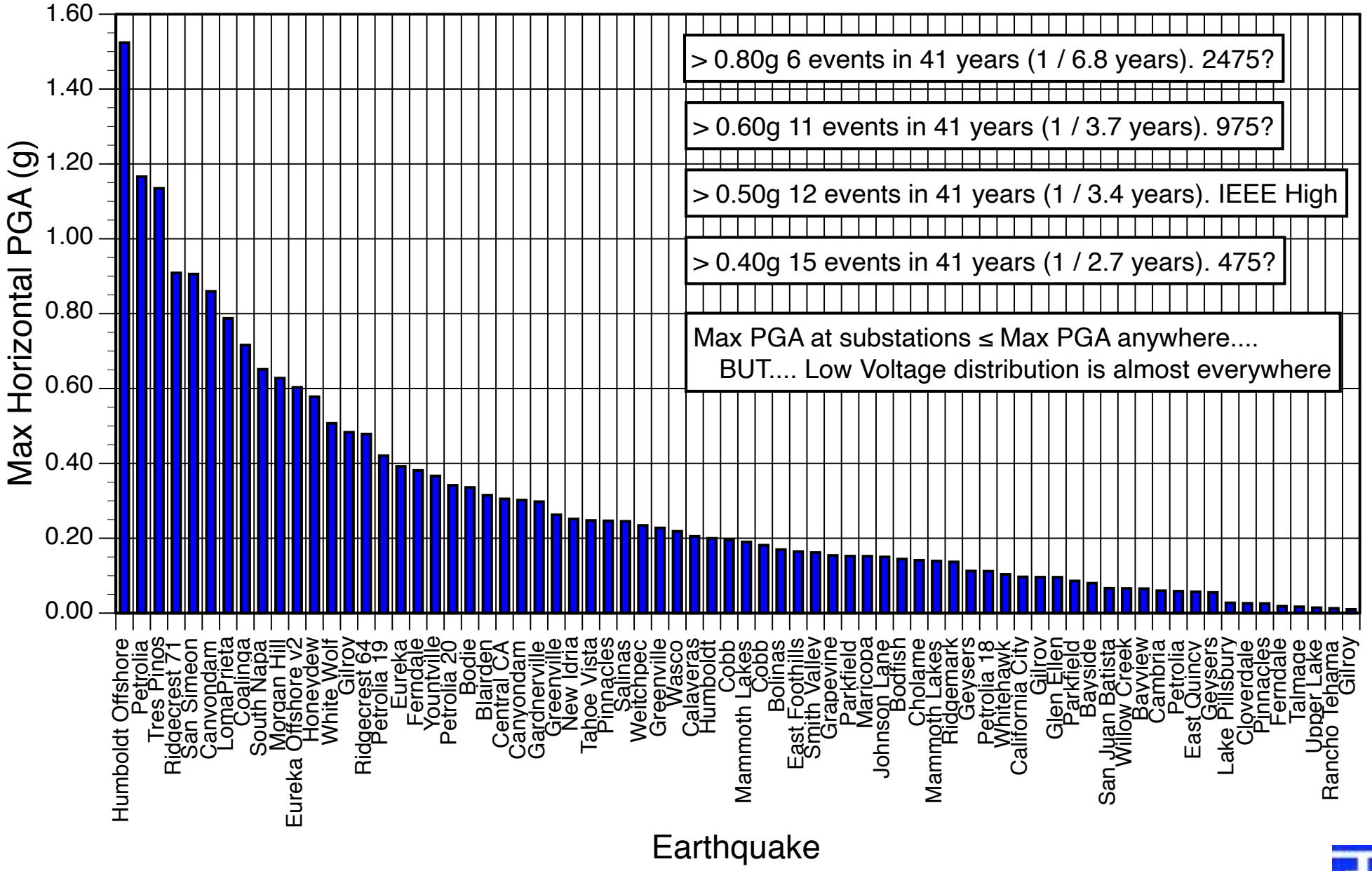


Computed using ShakeMaps (Max H1, H2)


Magnitude of 72 Events
Earthquake Magnitude M
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
7/21/52
1/27/80
11/8/80
4/24/84
3/31/86
8/17/91
7/11/92
9/12/94
12/28/95
5/15/99
1/11/00
8/10/01
4/28/02
6/17/02
12/23/03
9/28/04
9/29/04
6/26/05
5/12/06
8/2/06
4/18/07
10/31/07
4/29/08
1/10/10
8/27/11
2/13/12
10/20/12
5/24/13
8/24/14
1/28/15
7/21/16
3/17/17
3/22/18
7/4/19
10/15/19
3/20/20
Earthquake Date

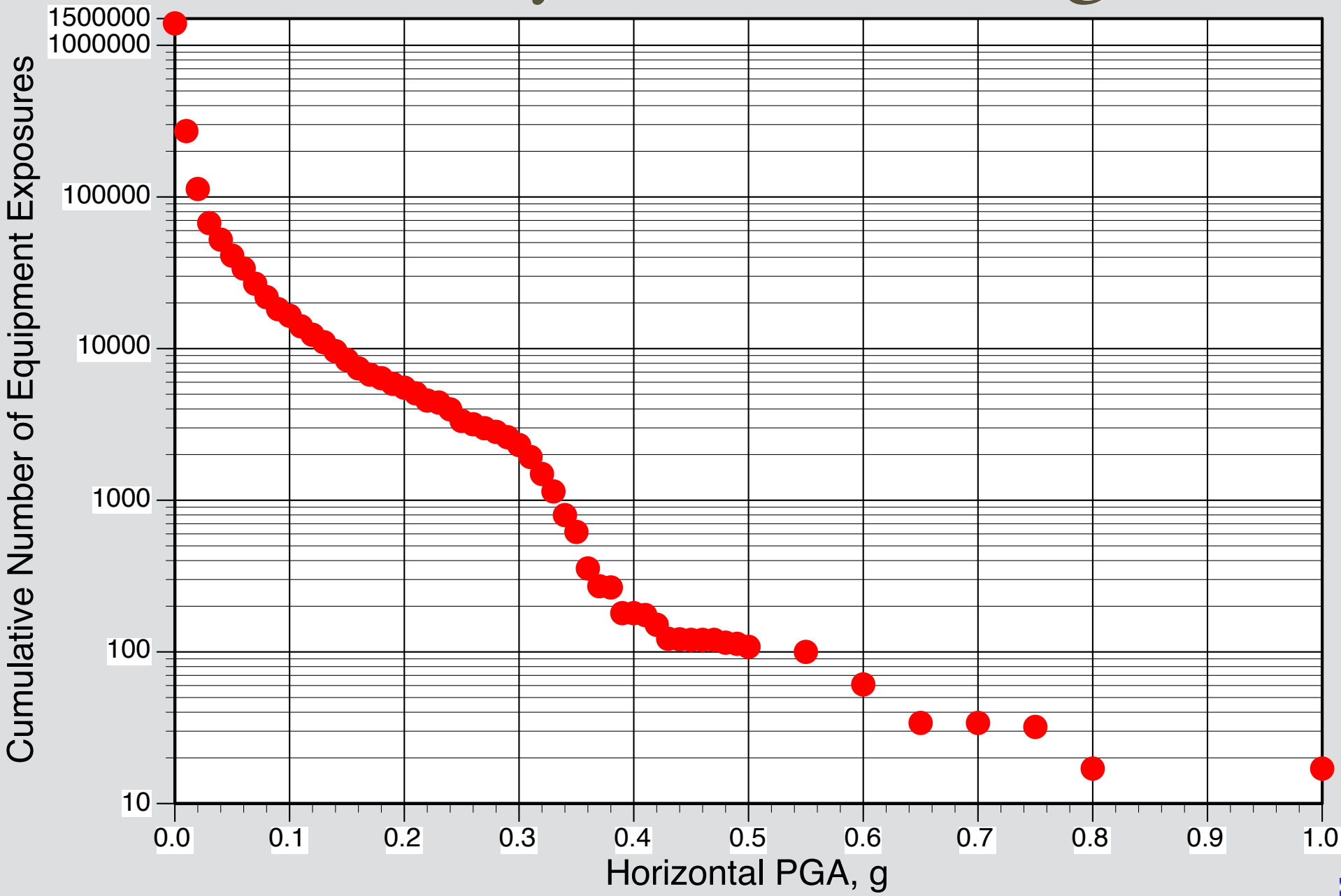

Count by Magnitude, Number of Events
Number of Events 1952, 1980-2021
0
1
2
3
4
5
6
7
8
9
7.2
7.1
6.9
6.5
6.4
6.3
6.2
6.1
6
5.8
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5
4.9
4.8
4.7
4.6
4.5
Magnitude

Maximum PGA, Anywhere in ShakeMap



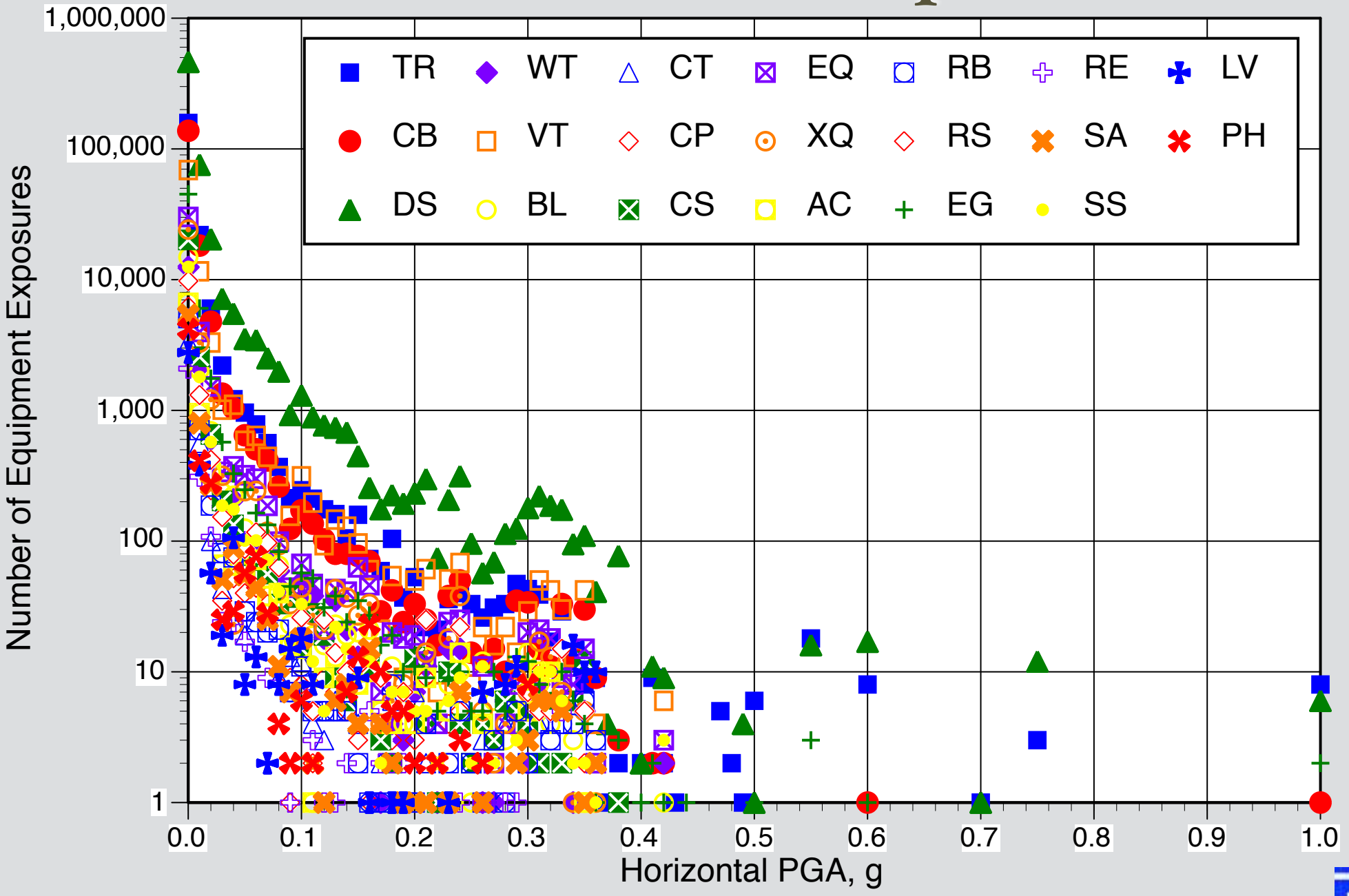
Computed using ShakeMaps (Max H1, H2)

20 Classes - By Bin, Running Count



Bin size = 0.01g [≤ 0.50g]; 0.05g [0.55 - 0.80g]; 0.20g [1.0g]
By Record

20 Classes - All Exposures



Bin size = 0.01g [≤ 0.50g]; 0.05g [0.55 - 0.80g]; 0.20g [1.0g]
By Record

SERA_051721

1 / 22531 Found (Unsorted)

Records | Show All | New Record | Delete Record | Find | Sort | Share | Search

Layout: Equipment Review | View As: | Preview | Edit Layout

Substation Name | Substation_ID 666 | ComponentID 6223 | Latitude_DD | Longitude_DD

Voltage 115 | Tag Number(s) 140 | Number Similar 1 | Fragility ID 940 | AA CB

SF6 Composite ABB Asea Brown Boveri

SERA_Position | SERA_T_Line | Voltage 115 | CircuitID 255 | Description CB

Tie1_ID | Tie2_ID | Tie3_ID | Stack1 RS-Small 3-way | Stack2 | PGD Stack for Settlement

Photo1 | Photo2 | Photo3 | Photo4 | Photo5 | Photo1_LR | Photo2_LR | Photo3_LR | Photo 4_LR | Photo 5_LR | Site Map

Busiwork failed in 2007 EQ

Original Photo: 1024 w x 681 h | Thumbnail Photo: 1024 w x 768 h

NFM	Damage State Description	Median	Beta	Freq	Low G	Function	Life Safety	Group	ST_Cost	LT_Cost	Duration	Backup	BSE	DSC
1	Bushing Failure	1.50	0.30	33.00	0.35	1.0	0	1	$2,000	$100,000	0	0	0	0

Last Edit Date 4/20/2021 | Count of times this record has been modified 25

UpgradeCostSelection $0 | Total_Items 1

Equipment Tag Number | Substation_

PGE_Location | PGE_Description | Cost_Assigned | Site in SERA_Model Yes | Replaced | Edit Date

ISO Criticality ISO Non Critical

Manufacturer Asea Brown Boveri | Model Number 121PM6330 | Serial Number | Part No

Install Date 11/1/2000 | Purchase Date 1/1/2000 | Manufactured Date 2/2/2000 | Age | Years

PGE_Voltage 115,000 | Total Weight Lbs 6,587 | Phases | Cost historic | Cost 2010

Interrupt Medium SF6 | Amps 3000 | Oil Main Gals | Oil Total Gals | LTC | Impedance (Pct) | Cooling Type | Equipment Sub Type

Primary Voltage kV | Secondary Voltage kV | Tertiary Voltage kV | Max MVA | Rating 1 MVA | Rating 2 MVA | Nameplate MVA | Temp Rise °C | Primary Connection

SysStatus | UserStatus | Year of Manufacture | TR_ComponentID

Results (Scenario) | Results (ShakeMap)

Event Name	Magnitude	Event Date	1=Yes 0= No or ? Equipment In Service	Median Results PGA	Number Damaged	Number Function Failures	ST_Cost	LT_Cost	Life Safety	84th Results PGA	Number Damaged	Number Function Failures	ST_Cost	LT_Cost	Life Safety	Observed Damage State Functional	Observed Damage State Any
LomaPrieta	6.9	10/18/1989	0	0.209	0.00	0.000	$0	$0	0.0	0.303	0.00	0.000	$0	$0	0.0	Yes	Yes
Morgan Hill	6.2	4/24/1984	0	0.120	0.00	0.000	$0	$0	0.0	0.192	0.00	0.000	$0	$0	0.0	Yes	Yes
Greenville	5.8	1/27/1980	0	0.073	0.00	0.000	$0	$0	0.0	0.125	0.00	0.000	$0	$0	0.0	Yes	Yes
Greenville	5.8	1/24/1980	0	0.073	0.00	0.000	$0	$0	0.0	0.123	0.00	0.000	$0	$0	0.0	Yes	Yes
Calaveras	5.6	3/31/1986	0	0.062	0.00	0.000	$0	$0	0.0	0.109	0.00	0.000	$0	$0	0.0	Yes	Yes
East Foothills	5.5	10/31/2007	1	0.047	0.00	0.000	$0	$0	0.0	0.083	0.00	0.000	$0	$0	0.0	Yes	Yes
Gilroy	4.9	5/13/2002	1	0.016	0.00	0.000	$0	$0	0.0	0.030	0.00	0.000	$0	$0	0.0	Yes	Yes
Coalinga	6.3	5/2/1983	0	0.012	0.00	0.000	$0	$0	0.0	0.019	0.00	0.000	$0	$0	0.0	Yes	Yes
South Napa	6.0	8/24/2014	1	0.009	0.00	0.000	$0	$0	0.0	0.015	0.00	0.000	$0	$0	0.0	Yes	Yes
Ridgemark	5.4	1/26/1986	0	0.006	0.00	0.000	$0	$0	0.0	0.011	0.00	0.000	$0	$0	0.0	Yes	Yes
Yountville	5.0	9/3/2000	0	0.005	0.00	0.000	$0	$0	0.0	0.010	0.00	0.000	$0	$0	0.0	Yes	Yes
Salinas	5.1	8/31/1998	0	0.005	0.00	0.000	$0	$0	0.0	0.009	0.00	0.000	$0	$0	0.0	Yes	Yes
Gilroy	4.8	1/16/1993	0	0.004	0.00	0.000	$0	$0	0.0	0.007	0.00	0.000	$0	$0	0.0	Yes	Yes
Bolinas	4.6	8/1/1999	0	0.003	0.00	0.000	$0	$0	0.0	0.006	0.00	0.000	$0	$0	0.0	Yes	Yes
San Juan Bautista	4.5	1/1/2011	1	0.002	0.00	0.000	$0	$0	0.0	0.003	0.00	0.000	$0	$0	0.0	Yes	Yes

Recommendation

Bushing 500 kV | Bushing 230 kV | Bushing 115 kV

Recommendation Date | Priority Assuming High Hazard | Seismic Hazard 0.60 PGA (g) | UpgradeCostPer Item | UpgradeCostAllItem $0

Fragility Photo

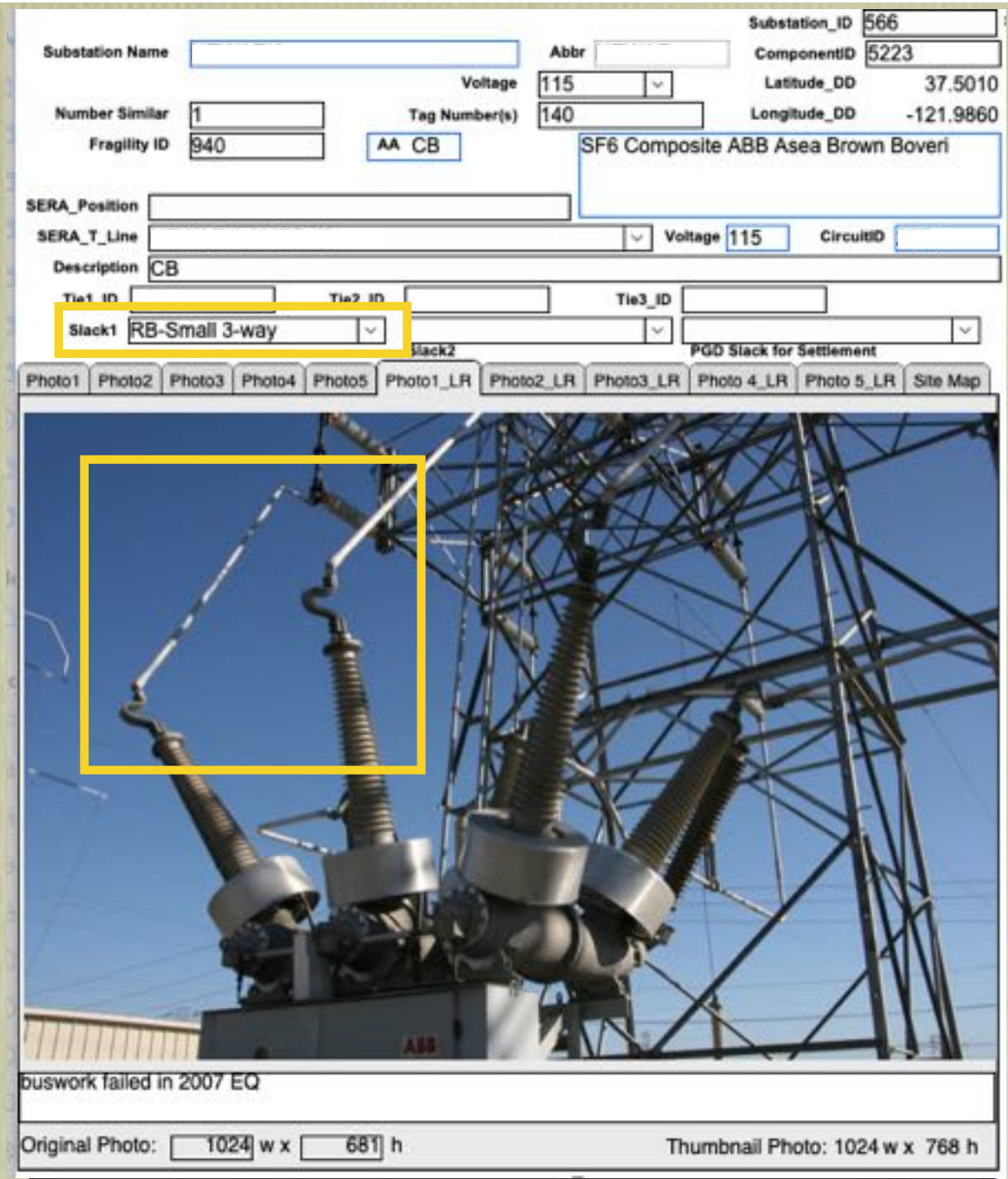
Photo1Path IMG_1867_6.jpg | Photo2Path | Photo3Path | Photo4Path | Photo5Path

Anyone think this is a seismically-Robust rigid bus detail?

The bus "broke".

The breaker had to be replaced

Two adjacent positions "targeted"



NFM	Damage State Description	Median	Beta	Freq	Low G	Function	Life Safety	Group	ST_Cost	LT_Cost	Duration	accDisp	SSG
1	Bushing Failure	1.50	0.30	33.00	0.35	1.0	0	1	$2,000	$100,000	0	0	0

Description	Value	Comment
1. Count of Items	3,231,904	Includes non-exposed items
2. Count of Items	632,313	Exposed Items, 0.0001g to 1.00g
3. Max PGA level	0.87g	
4. Max PGA level (5 or more items)	0.87g	
5. Min PGA level with any type of damage	0.04g	
6. Item count with any type of damage	109	
7. Beta (composite)	0.6530	
8. Fragility (Median)	2.71g	Least Squares Regression
9. Fragility (Median)	1.80g	Running Pct weight

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	210	0	0.32	0.32	0.32
230	2885	0	0.35	0.32	0.35
115	1856	0	0.32	0.32	0.32
69	0	0	0	0	0
LV	377	0	0.30	0.21	0.30

Table 5-3. Exposure and Damage Statistics, Air Core Reactors (AC)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	0	0	0	0	0
230	0	0	0	0	0
115	0	0	0	0	0
69	0	0	0	0	0
LV	4063	4	0.42	0.35	0.23

Table 5-4. Exposure and Damage Statistics, Buildings (BL)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	3312	0	0.33	0.32	0.33
230	9788	0	0.42	0.35	0.35
115	14390	1	0.38	0.35	0.04
69	9173	0	0.82	0.39	0.85
LV	468	0	0.25	0.25	0.25

Table 5-5. Exposure and Damage Statistics, Circuit Breakers (CB)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	1115	0	0.32	0.32	0.32
230	2328	0	0.35	0.35	0.35
115	1716	0	0.32	0.31	0.32
69	0	0	0	0	0
LV	0	0	0	0	0

Table 5-6. Exposure and Damage Statistics, Capacitors (CP)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	162	0	0.07	0.07	0.07
230	2586	3	0.35	0.35	0.33
115	7345	0	0.55	0.51	0.55
69	1803	0	0.35	0.35	0.35
LV	0	0	0	0	0

Table 5-7. Exposure and Damage Statistics, Circuit Switchers (CS)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	567	0	0.13	0.13	0.13
230	747	0	0.20	0.20	0.20
115	1004	0	0.33	0.33	0.33
69	96	0	0.31	0.30	0.31
LV	45	0	0.09	0.07	0.09

Table 5-8. Exposure and Damage Statistics, Current Transformers (CT)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	11395	18	0.33	0.33	0.31
230	110551	24	0.42	0.42	0.10
115	188334	3	0.55	0.55	0.10
69	100280	0	0.87	0.87	0.87
LV	201	0	0.26	0.34	0.25

Table 5-9. Exposure and Damage Statistics, Disconnect Switches (DS)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	0	0	0	0	0
230	0	0	0	0	0
115	0	0	0	0	0
69	0	0	0	0	0
LV	11121	0	0.87	0.52	0.87

Table 5-10. Exposure and Damage Statistics, Emergency Power (EG)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	230	0	0.24	0.05	0.24
230	468	0	0.33	0.19	0.33
115	60	0	0.33	0.10	0.30
69	0	0	0	0	0
LV	30	0	0.26	0.03	0.26

Table 5-15. Exposure and Damage Statistics, Reactors (RE)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	507	0	0.24	0.24	0.24
230	398	0	0.21	0.15	0.21
115	6738	0	0.35	0.35	0.35
69	0	0	0	0	0
LV	0	0	0	0	0

Table 5-16. Exposure and Damage Statistics, Risers (RS)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	1720	0	0.33	0.33	0.33
230	1277	0	0.35	0.32	0.35
115	1145	0	0.36	0.36	0.36
69	0	0	0	0	0
LV	0	0	0	0	0

Table 5-17. Exposure and Damage Statistics, Surge Arrestors (SA)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	0	0	0	0	0
230	0	0	0	0	0
115	66	0	0.02	0.02	0.02
69	52	0	0.19	0.07	0.19
LV	8170	0	0.42	0.42	0.42

Table 5-18. Exposure and Damage Statistics, Station Service (SS)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	785	10	0.33	0.33	0.23
230	4686	3	0.42	0.35	0.23
115	9578	2	0.55	0.41	0.09
69	13127	7	0.87	0.87	0.71
LV	8311	1	0.56	0.55	0.10

Table 5-19. Exposure and Damage Statistics, Power Transformers (TR)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	2860	9	0.33	0.33	0.31
230	22804	1	0.42	0.42	0.34
115	15315	0	0.35	0.35	0.35
69	568	0	0.34	0.34	0.34
LV	465	0	0.36	0.36	0.36

Table 5-20. Exposure and Damage Statistics, Voltage Transformers (VT)

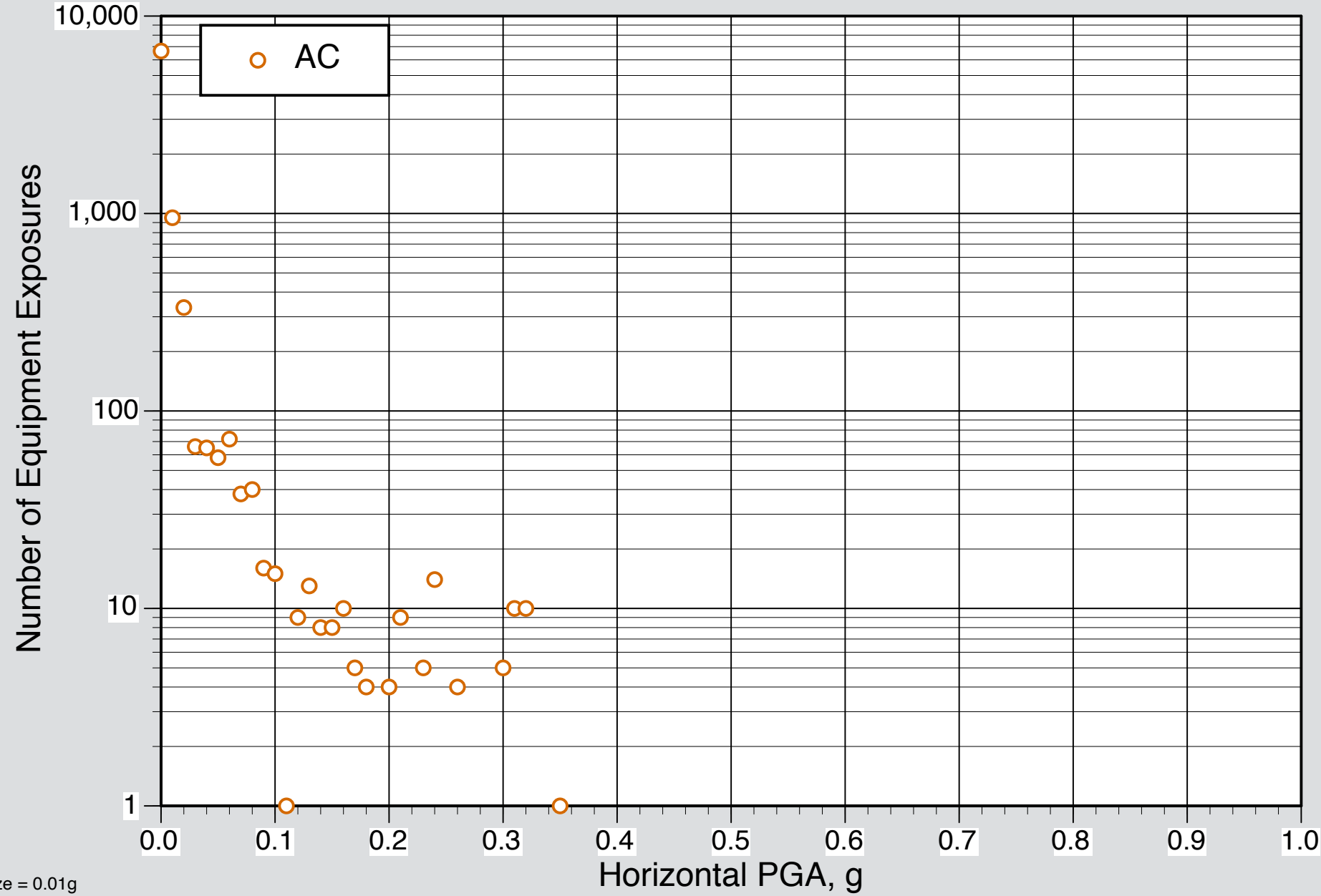
Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	665	0	0.33	0.32	0.33
230	2883	0	0.42	0.35	0.42
115	595	0	0.30	0.28	0.30
69	64	0	0.34	0.29	0.34
LV	0	0	0	0	0

Table 5-21. Exposure and Damage Statistics, Wave Traps (WT)

Voltage (kV)	Items Exposed > 0.0001g	Number Damaged	Max PGA g	Max PGA-5, g	PGA below which there is no Damage, g
500	0	0	0	0	0
230	16	0	0.08	0.03	0.08
115	0	0	0	0	0
69	0	0	0	0	0
LV	17007	9	0.39	0.39	0.27

Table 5-22. Exposure and Damage Statistics, Other Equipment (XQ)

Air Core Reactors (AC)



Bin size = 0.01g

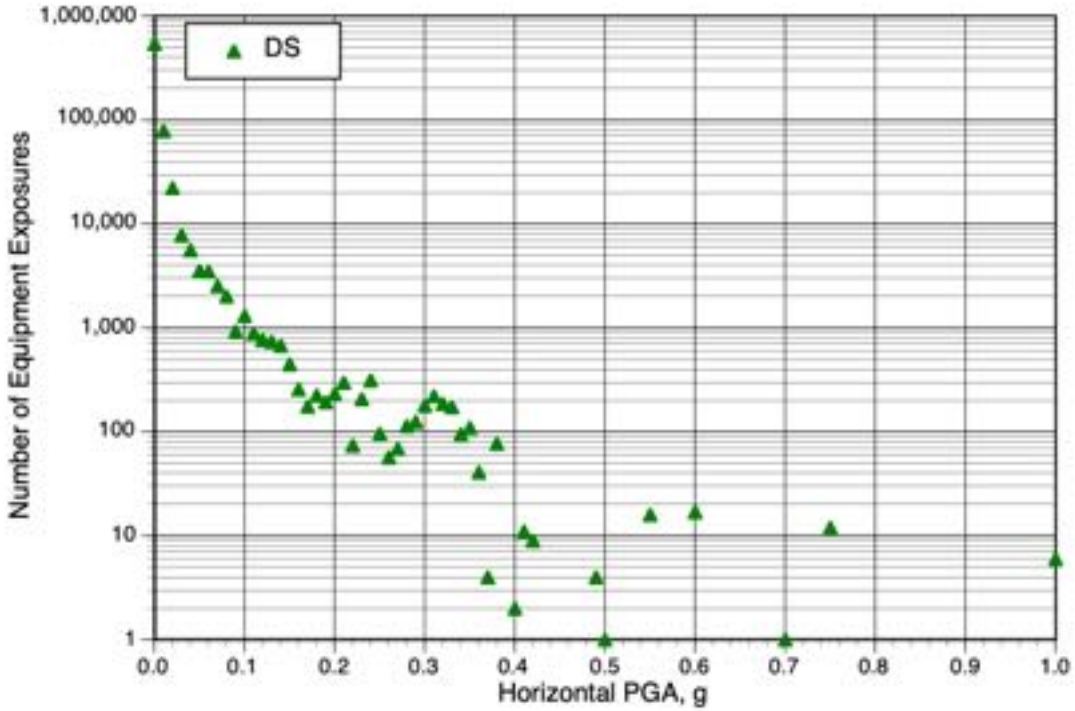


Figure 4-10.3. Number of exposures to various levels of PGA, Disconnect Switch Class

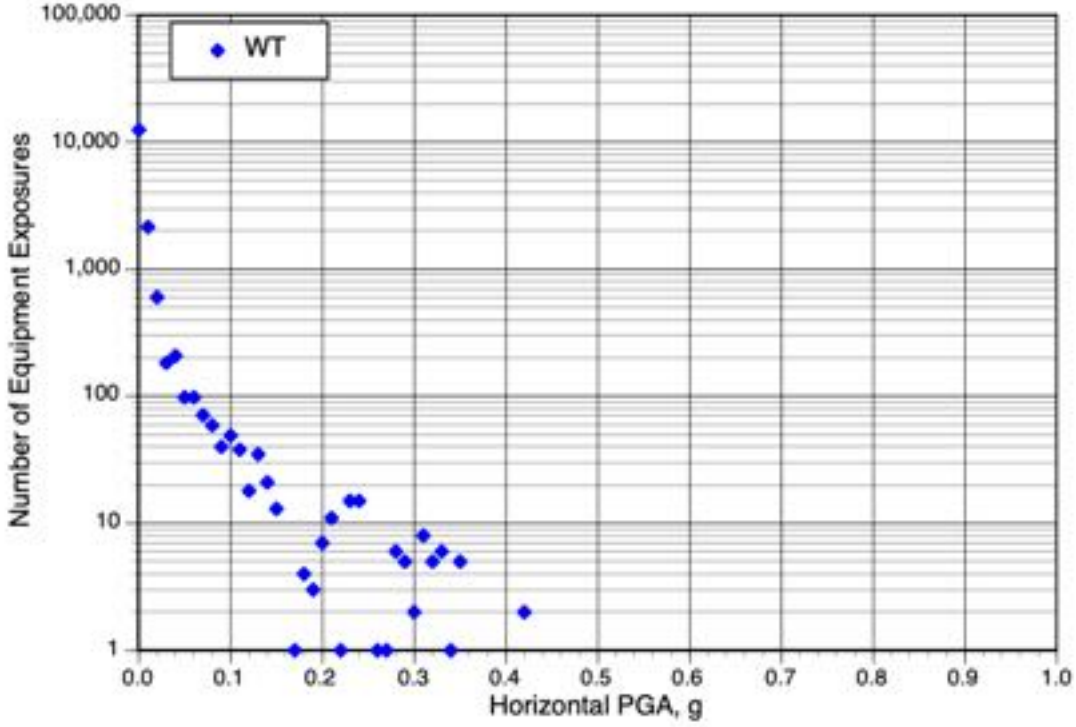
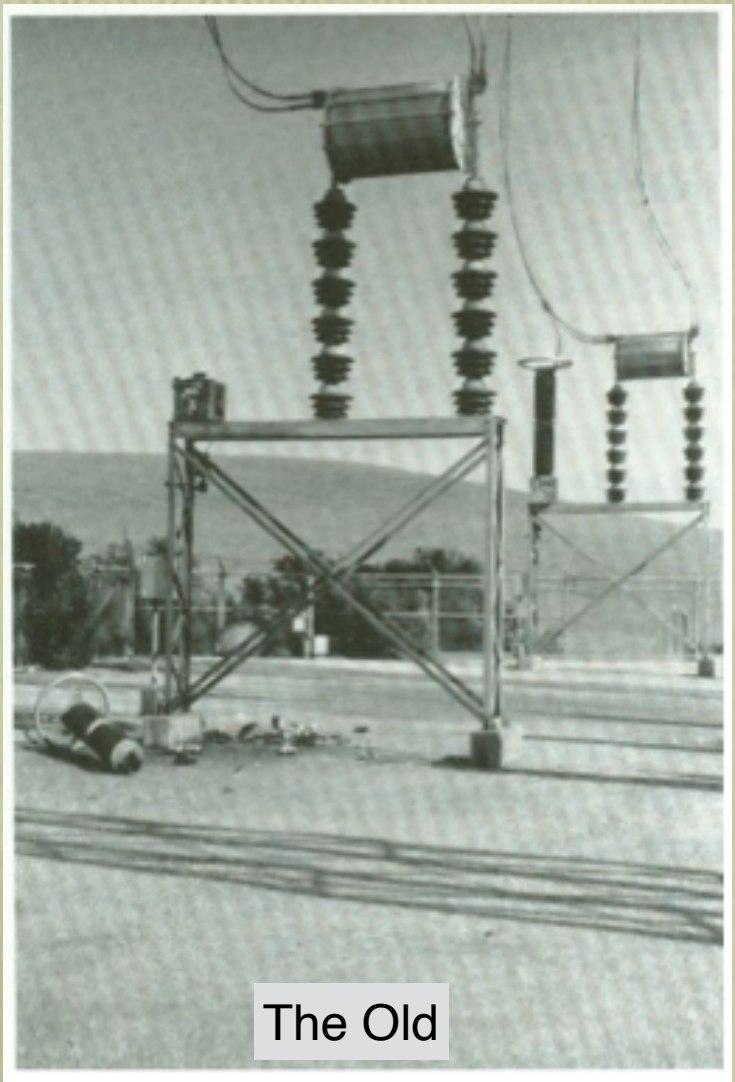


Figure 4-10.4. Number of exposures to various levels of PGA, Wave Trap Class

Bin size = 0.01g

230 - 500 kV Wave Trap, CCVTs


The Old


The Old

The Old CCVTs failed at PGA ~ 0.35g, but the WTs did not

New CCVTs: Median PGA = 1.46g, beta = 0.29.
Pretty darn tough.

F = had functional damage. D = had damage, but remained functional

SUMMARY over all records.

PGA Bin Low	PGA Bin High	Count	Running Count	hasD Count	hasF Count	hasFD Count	Running Count	Running Count	Running Count	hasD pct	hasF pct	hasFD pct	hasD pct	hasF pct	hasFD pct	Damage	Function	DAMorFUNC	D	F	FD
		PGA Maximum 0.87 g	PGA Max-S 0.87 g	PGA CutOff 0.09 g	PGA CutOff 0.04 g	PGA CutOff 0.04 g	-------- or lower --------- hasD	hasF	hasFD	-------has/Count--------						-- FRAGILITY MEDIANS (in g)--			-- Model Type ---- 0 = No data 1 = Tail Based 2 = HCLPF Based		
0.0000 to	0.0001 g	2599591	3231904	0	0	0	51	58	109	0.0000000	0.0000000	0.0000000	0.0000158	0.0000179	0.0000337	0.0000	0.0000	0.0000	0	0	0
0.0001 to	0.01 g	366015	632313	0	0	0	51	58	109	0.0000000	0.0000000	0.0000000	0.0000807	0.0000917	0.0001724	0.1175	0.1154	0.1037	1	1	1
0.01 to	0.02 g	184590	266298	0	0	0	51	58	109	0.0000000	0.0000000	0.0000000	0.0001915	0.0002178	0.0004093	0.2038	0.1989	0.1783	1	1	1
0.02 to	0.03 g	34637	161708	0	0	0	51	58	109	0.0000000	0.0000000	0.0000000	0.0003154	0.0003587	0.0006741	0.2803	0.2739	0.2437	1	1	1
0.03 to	0.04 g	27674	127071	0	0	0	51	58	109	0.0000000	0.0000000	0.0000000	0.0004014	0.0004564	0.0008578	0.3580	0.3489	0.3109	1	1	1
0.04 to	0.05 g	16865	99397	0	1	1	51	58	109	0.0000000	0.0000593	0.0000593	0.0005131	0.0005835	0.0010966	0.4269	0.4177	0.3704	1	1	1
0.05 to	0.06 g	17293	82532	0	0	0	51	57	108	0.0000000	0.0000000	0.0000000	0.0006179	0.0006906	0.0013086	0.4959	0.4848	0.4286	1	1	1
0.06 to	0.07 g	11483	65239	0	0	0	51	57	108	0.0000000	0.0000000	0.0000000	0.0007817	0.0008737	0.0016555	0.5537	0.5420	0.4778	1	1	1
0.07 to	0.08 g	8582	53756	0	0	0	51	57	108	0.0000000	0.0000000	0.0000000	0.0009487	0.0010603	0.0020091	0.6087	0.5963	0.5246	1	1	1
0.08 to	0.09 g	4129	45174	0	0	0	51	57	108	0.0000000	0.0000000	0.0000000	0.0011290	0.0012618	0.0023908	0.6630	0.6481	0.5692	1	1	1
0.09 to	0.10 g	5910	41045	1	0	1	51	57	108	0.0001692	0.0000000	0.0001692	0.0012425	0.0013887	0.0026313	0.7224	0.7058	0.6192	1	1	1
0.10 to	0.11 g	4003	35135	4	3	7	50	57	107	0.0009993	0.0007494	0.0017487	0.0014231	0.0016223	0.0030454	0.7730	0.7539	0.6612	1	1	1
0.11 to	0.12 g	3231	31132	0	0	0	46	54	100	0.0000000	0.0000000	0.0000000	0.0014776	0.0017345	0.0032121	0.8375	0.8109	0.7127	1	1	1
0.12 to	0.13 g	5006	27901	0	0	0	46	54	100	0.0000000	0.0000000	0.0000000	0.0016487	0.0019354	0.0035841	0.8880	0.8584	0.7532	1	1	1
0.13 to	0.14 g	2194	22895	0	0	0	46	54	100	0.0000000	0.0000000	0.0000000	0.0020092	0.0023586	0.0043678	0.9180	0.8881	0.7770	1	1	1
0.14 to	0.15 g	2298	20701	0	0	0	46	54	100	0.0000000	0.0000000	0.0000000	0.0022221	0.0026086	0.0048307	0.9639	0.9303	0.8134	1	1	1
0.15 to	0.16 g	1517	18403	0	0	0	46	54	100	0.0000000	0.0000000	0.0000000	0.0024996	0.0029343	0.0054339	1.0015	0.9694	0.8459	1	1	1
0.16 to	0.17 g	963	16886	0	0	0	46	54	100	0.0000000	0.0000000	0.0000000	0.0027242	0.0031979	0.0059221	1.0457	1.0107	0.8804	1	1	1
0.17 to	0.18 g	1628	15923	1	0	1	46	54	100	0.0006143	0.0000000	0.0006143	0.0028889	0.0033913	0.0062802	1.0942	1.0554	0.9189	1	1	1
0.18 to	0.19 g	864	14295	0	0	0	45	54	99	0.0000000	0.0000000	0.0000000	0.0031480	0.0037775	0.0069255	1.1337	1.0893	0.9496	1	1	1
0.19 to	0.20 g	1174	13431	0	0	0	45	54	99	0.0000000	0.0000000	0.0000000	0.0033505	0.0040205	0.0073710	1.1761	1.1314	0.9851	1	1	1
0.20 to	0.21 g	1352	12257	0	0	0	45	54	99	0.0000000	0.0000000	0.0000000	0.0036714	0.0044056	0.0080770	1.2109	1.1631	1.0106	1	1	1
0.21 to	0.22 g	312	10905	0	0	0	45	54	99	0.0000000	0.0000000	0.0000000	0.0041265	0.0049519	0.0090784	1.2373	1.1869	1.0308	1	1	1
0.22 to	0.23 g	1060	10593	0	0	0	45	54	99	0.0000000	0.0000000	0.0000000	0.0042481	0.0050977	0.0093458	1.2850	1.2333	1.0702	1	1	1
0.23 to	0.24 g	1679	9533	6	4	10	45	54	99	0.0035736	0.0023824	0.0059559	0.0047204	0.0056645	0.0103850	1.3075	1.2565	1.0870	1	1	1
0.24 to	0.25 g	399	7854	0	0	0	39	50	89	0.0000000	0.0000000	0.0000000	0.0049656	0.0063662	0.0113318	1.3480	1.2726	1.1085	1	1	1
0.25 to	0.26 g	399	7455	0	0	0	39	50	89	0.0000000	0.0000000	0.0000000	0.0052314	0.0067069	0.0119383	1.3863	1.3088	1.1386	1	1	1
0.26 to	0.27 g	317	7056	3	0	3	39	50	89	0.0094637	0.0000000	0.0094637	0.0055272	0.0070862	0.0126134	1.4218	1.3423	1.1661	1	1	1
0.27 to	0.28 g	511	6739	5	0	5	36	50	86	0.0097847	0.0000000	0.0097847	0.0053420	0.0074195	0.0127615	1.4860	1.3769	1.2056	1	1	1
0.28 to	0.29 g	612	6228	7	0	7	31	50	81	0.0114379	0.0000000	0.0114379	0.0049775	0.0080283	0.0130058	1.5629	1.3979	1.2425	1	1	1
0.29 to	0.30 g	932	5616	0	0	0	24	50	74	0.0000000	0.0000000	0.0000000	0.0042735	0.0089031	0.0131766	1.6737	1.4120	1.2808	1	1	1
0.30 to	0.31 g	1055	4684	0	0	0	24	50	74	0.0000000	0.0000000	0.0000000	0.0051238	0.0106746	0.0157985	1.6604	1.3936	1.2638	1	1	1
0.31 to	0.32 g	883	3629	7	10	17	24	50	74	0.0079275	0.0113250	0.0192525	0.0066134	0.0137779	0.0203913	1.6158	1.3494	1.2190	1	1	1
0.32 to	0.33 g	834	2746	3	35	38	17	40	57	0.0035971	0.0419664	0.0455635	0.0061908	0.0145666	0.0207575	1.6899	1.3729	1.2510	1	1	1
0.33 to	0.34 g	397	1912	7	0	7	14	5	19	0.0176322	0.0000000	0.0176322	0.0073222	0.0026151	0.0099372	1.6773	2.1078	1.5580	1	1	1
0.34 to	0.35 g	626	1515	1	1	2	7	5	12	0.0015974	0.0015974	0.0031949	0.0046205	0.0033003	0.0079208	1.9158	2.0657	1.6931	1	1	1
0.35 to	0.36 g	174	889	3	0	3	6	4	10	0.0172414	0.0000000	0.0172414	0.0067492	0.0044994	0.0112486	1.8097	1.9837	1.5990	1	1	1
0.36 to	0.37 g	13	715	0	0	0	3	4	7	0.0000000	0.0000000	0.0000000	0.0041958	0.0055944	0.0097902	2.0730	1.9429	1.7019	1	1	1
0.37 to	0.38 g	248	702	0	0	0	3	4	7	0.0000000	0.0000000	0.0000000	0.0042735	0.0056980	0.0099715	2.1200	1.9867	1.7397	1	1	1
0.38 to	0.39 g	24	454	0	3	3	3	4	7	0.0000000	0.1250000	0.1250000	0.0066879	0.0088106	0.0154185	1.9696	1.8400	1.5999	1	1	1
0.39 to	0.40 g	9	430	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0069767	0.0023256	0.0093023	1.9958	2.5454	1.8633	1	1	1
0.40 to	0.41 g	46	421	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0071259	0.0023753	0.0095012	2.0357	2.5968	1.9001	1	1	1
0.41 to	0.42 g	62	375	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0080000	0.0026667	0.0106667	2.0264	2.5941	1.8885	1	1	1
0.42 to	0.43 g	1	313	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0095847	0.0031949	0.0127796	1.9884	2.5571	1.8508	1	1	1
0.43 to	0.44 g	1	312	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0096154	0.0032051	0.0128205	2.0331	2.6146	1.8923	1	1	1
0.44 to	0.45 g	0	311	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0096463	0.0032154	0.0128617	2.0776	2.6721	1.9337	1	1	1
0.45 to	0.46 g	0	311	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0096463	0.0032154	0.0128617	2.1238	2.7315	1.9766	1	1	1
0.46 to	0.47 g	5	311	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0096463	0.0032154	0.0128617	2.1699	2.7908	2.0196	1	1	1
0.47 to	0.48 g	2	306	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0098039	0.0032680	0.0130719	2.2071	2.8395	2.0537	1	1	1
0.48 to	0.49 g	13	304	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0098684	0.0032895	0.0131579	2.2493	2.8942	2.0928	1	1	1
0.49 to	0.50 g	10	291	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0103093	0.0034364	0.0137457	2.2691	2.9223	2.1099	1	1	1
0.50 to	0.51 g	105	281	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0106762	0.0035587	0.0142349	2.2926	2.9591	2.1334	1	1	1
0.51 to	0.52 g	7	176	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0170455	0.0056818	0.0227273	2.0768	2.7205	1.9201	1	1	1
0.52 to	0.53 g	3	169	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0177515	0.0059172	0.0236686	2.0922	2.7455	1.9369	1	1	1
0.53 to	0.54 g	2	166	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0180723	0.0060241	0.0240964	2.1218	2.7847	1.9642	1	1	1
0.54 to	0.55 g	31	164	0	0	0	3	1	4	0.0000000	0.0000000	0.0000000	0.0182927	0.0060976	0.0243902	2.1548	2.8275	1.9942	1	1	1
0.55 to	0.56 g	52	133	0	1	1	3	1	4	0.0000000	0.0192308	0.0192308	0.0225564	0.0075188	0.0300752	2.0725	2.7449	1.9129	1	1	1

SUMMARY for TYPE= CB

VOLTAGE CLASS	TOTAL Exposed >0.0001g number	TOTAL Damaged Dam/Func number	PGA MAX g	PGA MAX-S g	PGA CutOff hasD g	PGA CutOff hasF g	PGA CutOff hasFD g
500 kV	3312	0	0.33	0.32	0.33	0.33	0.33
230 kV	9788	0	0.42	0.35	0.42	0.42	0.42
115 kV	14390	1	0.38	0.35	0.38	0.04	0.04
69 kV	9173	0	0.85	0.39	0.85	0.85	0.85
Low V	468	0	0.25	0.25	0.25	0.25	0.25

SUMMARY for TYPE= CB

PGA Bin Low	PGA Bin High	PGA Max 0.33 g 500 kV Count	PGA Max-S 0.32 g 500 kV Running Count	PGA Max 0.42 g 230 kV Count	PGA Max-S 0.35 g 230 kV Running Count	PGA Max 0.38 g 115 kV Count	PGA Max-S 0.35 g 115 kV Running Count	PGA Max 0.85 g 69 kV Count	PGA Max-S 0.39 g 69 kV Running Count	PGA Max 0.25 g Low V Count	PGA Max-S 0.25 g Low V Running Count
0.0000 to	0.0001 g	16449	19761	46957	56745	69040	83430	42038	51211	1502	1970
0.0001 to	0.01 g	2370	3312	6181	9788	8442	14390	5744	9173	243	468
0.01 to	0.02 g	543	942	1650	3607	2610	5948	1461	3429	64	225
0.02 to	0.03 g	78	399	403	1957	648	3338	555	1968	32	161
0.03 to	0.04 g	135	321	310	1554	567	2690	379	1413	15	129
0.04 to	0.05 g	66	186	187	1244	479	2123	167	1034	22	114
0.05 to	0.06 g	3	120	282	1057	396	1644	163	867	22	92
0.06 to	0.07 g	45	117	192	775	234	1248	104	704	4	70
0.07 to	0.08 g	27	72	78	583	142	1014	103	600	20	66
0.08 to	0.09 g	3	45	50	505	47	872	50	497	18	46
0.09 to	0.10 g	9	42	82	455	109	825	51	447	2	28
0.10 to	0.11 g	0	33	40	373	64	716	53	396	0	26
0.11 to	0.12 g	0	33	49	333	46	652	44	343	0	26
0.12 to	0.13 g	21	33	31	284	69	606	28	299	4	26
0.13 to	0.14 g	0	12	4	253	89	537	33	271	0	22
0.14 to	0.15 g	0	12	22	249	96	448	21	238	0	22
0.15 to	0.16 g	0	12	14	227	70	352	12	217	0	22
0.16 to	0.17 g	0	12	5	213	15	282	21	205	0	22
0.17 to	0.18 g	0	12	7	208	12	267	17	184	2	22
0.18 to	0.19 g	0	12	20	201	5	255	11	167	0	20
0.19 to	0.20 g	0	12	18	181	12	250	11	156	2	20
0.20 to	0.21 g	0	12	4	163	29	238	6	145	0	18
0.21 to	0.22 g	0	12	0	159	12	209	6	139	0	18
0.22 to	0.23 g	0	12	44	159	5	197	9	133	0	18
0.23 to	0.24 g	0	12	47	115	29	192	10	124	0	18
0.24 to	0.25 g	0	12	0	68	3	163	7	114	18	18
0.25 to	0.26 g	0	12	0	68	20	160	4	107	0	0
0.26 to	0.27 g	0	12	0	68	8	140	11	103	0	0
0.27 to	0.28 g	0	12	0	68	4	132	7	92	0	0
0.28 to	0.29 g	0	12	7	68	4	128	26	85	0	0
0.29 to	0.30 g	0	12	9	61	37	124	12	59	0	0
0.30 to	0.31 g	0	12	2	52	14	87	7	47	0	0
0.31 to	0.32 g	9	12	4	50	10	73	0	40	0	0
0.32 to	0.33 g	3	3	33	46	42	63	7	40	0	0
0.33 to	0.34 g	0	0	3	13	2	21	8	33	0	0
0.34 to	0.35 g	0	0	8	10	18	19	8	25	0	0
0.35 to	0.36 g	0	0	0	2	0	1	9	17	0	0
0.36 to	0.37 g	0	0	0	2	0	1	0	8	0	0
0.37 to	0.38 g	0	0	0	2	1	1	2	8	0	0
0.38 to	0.39 g	0	0	0	2	0	0	2	6	0	0
0.39 to	0.40 g	0	0	0	2	0	0	0	4	0	0
0.40 to	0.41 g	0	0	0	2	0	0	2	4	0	0
0.41 to	0.42 g	0	0	2	2	0	0	0	2	0	0
0.42 to	0.43 g	0	0	0	0	0	0	0	2	0	0
0.43 to	0.44 g	0	0	0	0	0	0	0	2	0	0
0.44 to	0.45 g	0	0	0	0	0	0	0	2	0	0
0.45 to	0.46 g	0	0	0	0	0	0	0	2	0	0
0.46 to	0.47 g	0	0	0	0	0	0	0	2	0	0
0.47 to	0.48 g	0	0	0	0	0	0	0	2	0	0
0.48 to	0.49 g	0	0	0	0	0	0	0	2	0	0

Figure 5-1 shows a photo and SERA database record for FagilityID = 111.

Equipment Abbreviation: EQ Voltage (kv): 0 Substation:

Equipment Description: Desk top or other computer monitors (unanchored)

Photo 1 | Photo 2 | Photo 3 | Photo 1_LR | Photo 2_LR | Photo 3_LR

Fragility ID: 111 NFMODE: 1 Slack Frequency: Hz

FIELD RATINGS

Anchorage Rating
Bushing High
Bushing Low
Rating Non-Transformer
Radiator Rating
Surge Arrestor High
Surge Arrestor Low
Transformer Weight: pounds
Self Supported Radiator Weight: pounds
Anchor Description

Fragility Comments

PGE Book Number
BPA Book Number
BCH Book Number
SDGE Book Number

NFM	Damage State Description	Median	Beta	Freq	Low G	Function	Life Safety	Group	ST_Cost	LT_Cost	Duration	accDisp	SSG	DSC
1	Monitor falls to floor	0.35	0.30	33.0	0.10	1.0	0	1	$1,000	$2,000	0	0	0	0

Figure 5-1. Desk Top Monitor Unanchored, Fragility Model 111

PGA Bin (g)	Items Exposed Running Count	D No. Damaged and Functional	F No. Damaged and non-Functional	Fragility, D PGA (g)	Fragility, F PGA (g)
[1]	[2]	[3]	[4]	[5]	[6]
0.00	5276	3	0	-	-
0.01	1081	3	0	0.06	0.04
0.02	509	3	0	0.10	0.08
0.03	392	3	0	0.15	0.12
0.04	293	3	0	0.18	0.16
0.05	183	3	0	0.20	0.20
0.06	143	3	0	0.23	0.24
0.07	106	3	0	0.24	0.28
0.08	102	3	0	0.27	0.32
0.09	93	3	0	0.30	0.36
0.10	89	3	0	0.33	0.40
0.11	86	3	0	0.36	0.44
0.12	79	3	0	0.38	0.48
0.13	77	3	0	0.41	0.52
0.14	39	3	0	0.36	0.56
0.15	39	3	0	0.38	0.60
0.16	29	3	0	0.37	0.64
0.17	29	3	0	0.39	0.68
0.18	29	3	0	0.41	0.72
0.19	29	3	0	0.43	0.76
0.20	29	3	0	0.46	0.80
0.21	29	3	0	0.48	0.84
0.22	27	3	0	0.49	0.88
0.23	27	3	0	0.51	0.92
0.24	25	3	0	0.52	0.96
0.25	24	3	0	0.53	1.00
0.26	24	3	0	0.55	1.04
0.27	19	3	0	0.52	1.05
0.28	19	3	0	0.54	1.09
0.29	18	2	0	0.64	1.10
0.30	15	2	0	0.62	1.05
0.31	10	2	0	0.54	0.93
0.32	8	2	0	0.50	0.83
0.33	6	2	0	0.44	0.73
0.34	6	2	0	0.45	0.75
0.35	4	1	0	0.54	0.61
0.36	1	1	0	0.02	0.36
Fragility			Average	0.39	0.63
			Weighted	0.45	0.7
			Max	0.64	1.1

Item	Value	Comment
FragilityID	4	The SERA FragilityID Number
Type	DS	Disconnect Switch
Voltage	230	kV
Item Count	20736	Total items
Count > 0.0001g	3663	Number of Items exposed to PGA > 0.0001g
Count > 0.05g	537	Number of Items exposed to PGA > 0.05g
Count > 0.10g	219	Number of Items exposed to PGA > 0.10g
Count > 0.20g	42	Number of Items exposed to PGA > 0.20g
Max PGA g	0.32g	Highest PGA level any item was exposed to
Max-5 PGA g	0.32g	Highest PGA level at least 5 items were exposed to
Count Damage	0	Number of items damaged and remained functional
Count FuncDam	0	Number of items damaged and not functional
Count F or D	0	Number of items damaged and either func. or non-func.
PGA Cutoff hasD, g	0.32g	Highest PGA level below which there was no damage
PGA Cutoff hasF, g	0.32g	Highest PGA level below which there was no func. damage
PGA Cutoff hasFD, g	0.32g	Highest PGA level below which there was no damage: f or non f
Fragility D, g	0.85g	Weighted fragility based on damage but functional
Fragility F, g	0.85g	Weighted fragility based on damage non-functional
Fragility FD, g	0.85g	Weighted fragility based on damage, functional or non-functional
Description		Post Insulator, Double Height, Braced Frame

IEEE 693 vs Reality

- IEEE 693 is geared to qualify equipment for PGA = 0.50g, with "margin"
- Margin is good. Otherwise, we get regular widespread failures
- A few failures in a single earthquake (earthquake sequence) is "acceptable".

Fragility Based on Test Data

Type	Voltage Class KV	Median PGA, g	Beta	Slack Frequency Hz
DS	500	1.01	0.43	3.0
SA	500	4.44	0.29	1.6
DS	500	0.95	0.43	2.7
CB	500	2.43	0.30	8.3
DS	500	1.49	0.38	4.3
CB	500	3.33	0.28	11.5
CB	500	3.33	0.28	7.8
CB	115	2.35	0.31	14.2
CB	230	2.71	0.31	6.3
CB	115	1.21	0.27	6.8
CB	115	1.70	0.30	6.8
CB	230	1.47	0.31	11.1
DS	230	1.29	0.29	5.0
CB	115	0.79	0.34	14.2
DS	500	1.21	0.29	2.6
CB	500	1.96	0.38	0.6
DS	230	1.91	0.29	
CS	115	1.46	0.29	
CS	115	1.29	0.29	
CS	230	1.90	0.29	
CS	60	1.72	0.29	
CS	115	1.82	0.29	
DS	500	1.14	0.29	4.8
CB	230	1.08	0.31	3.9
CB	230	1.29	0.31	6.8
CB	115	1.25	0.34	10.3
DS	500	1.97	0.29	2.9
DS	500			4.0
CB	500	1.25	0.27	
DS	230	0.43	0.35	7.5
DS	230	2.27	0.29	5.7
DS	230	6.09	1.04	7.0
DS	230	1.82	0.29	4.1
CB	230	2.96	0.31	3.4
DS	500	1.16	0.27	2.6
SA	500	6.02	0.29	1.6
CB	115	1.68	0.31	7.3
CB	60	2.53	0.31	19.5
CB	115	1.65	0.31	2.3
CB	115	1.02	0.31	14.2

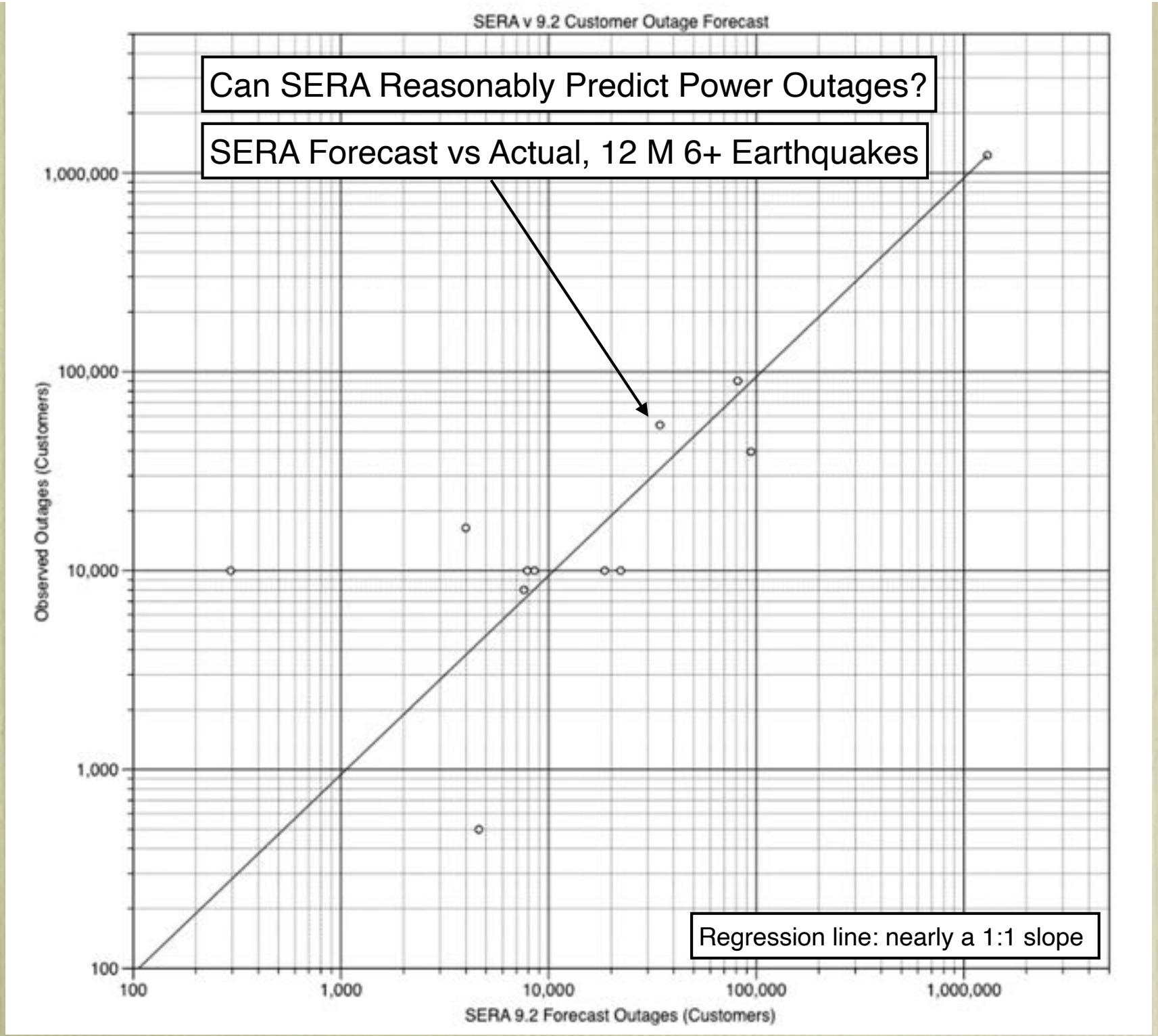
Type	Voltage Class KV	Median PGA, g	Beta	Slack Frequency Hz
CB	230	2.71	0.31	3.1
CB	230	1.96	0.37	5.5
SA	230	6.83	0.30	3.1
CB	115	0.88	0.31	6.6
DS	500	1.38	0.29	2.5
SA	500	1.17	0.29	2.0
CB	115	1.37	0.31	7.7
CB	500	1.71	0.28	6.0
DS	115	3.99	0.35	8.3
CB	34	1.05	0.34	5.3
DS	115	4.59	0.35	8.4
DS	500	1.78	0.29	3.5
DS	115	8.07	0.35	10.1
CB	500	1.81	0.35	0.9
DS	500	2.97	0.29	4.3
CB	60	1.41	0.31	7.4
CB	115	1.61	0.31	7.7
CB	230	2.75	0.31	4.7
DS	500	1.84	0.29	3.4
CB	60	1.55	0.34	8.0
DS	500	2.97	0.29	4.3
SA	230	2.95	0.29	3.9
DS	230	1.50	0.29	8.0
CS	500	1.49	0.29	2.7
DS	230			
DS	500	0.92	0.42	6.2
DS	500	1.08	0.29	2.5
DS	500	0.94	0.29	1.8
DS	500	0.95	0.29	1.8
PH	115	0.55	0.29	
PH	230	0.28	0.29	
CB	230	3.03	0.31	3.3
CB	60	1.14	0.34	21.9

Modern, mostly post IEEE 693

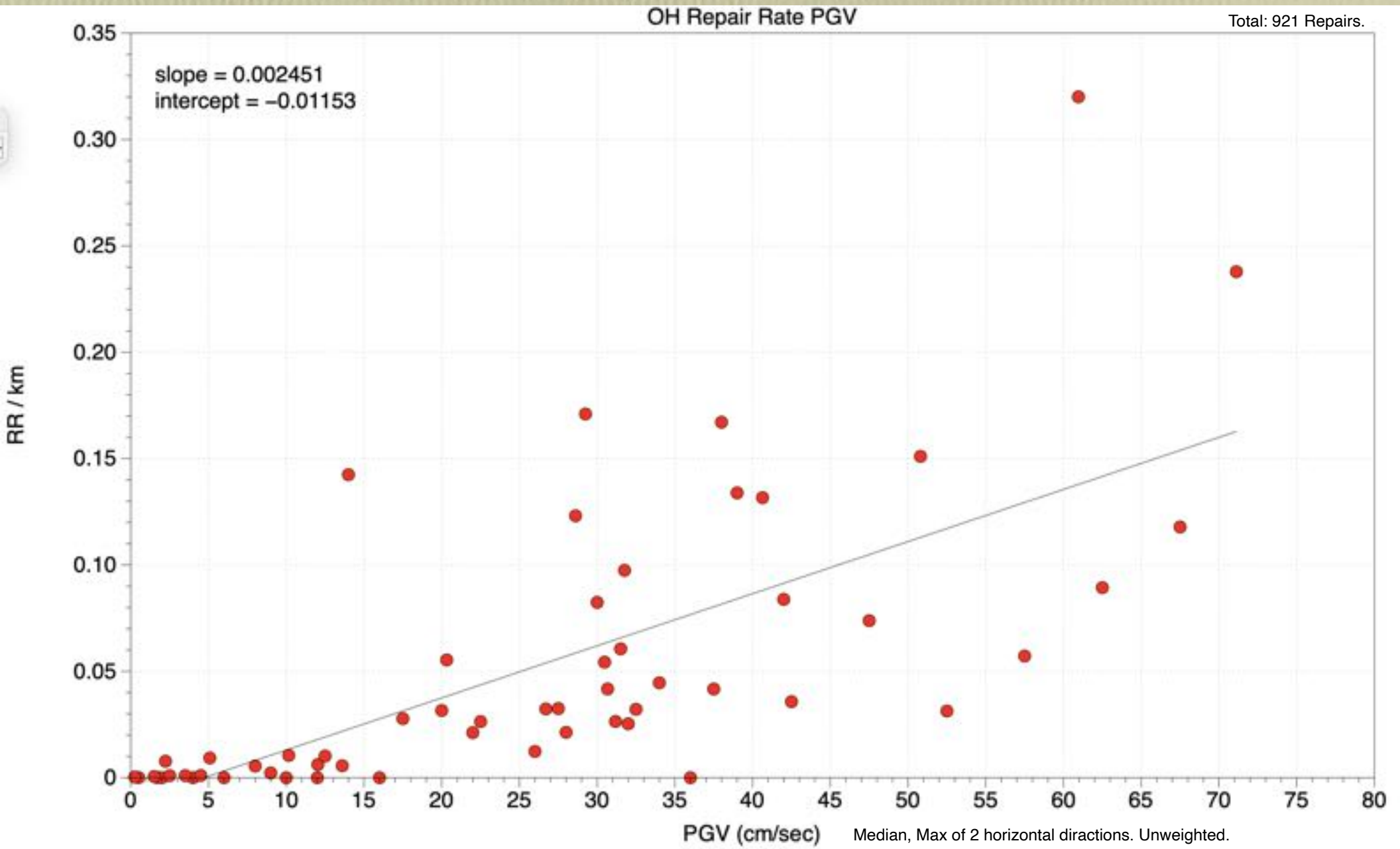
Component	34 kV	60 kV	115 kV	230 kV	500 kV
CB	1.05	1.66	1.41	2.22	2.26
CS		1.72	1.52	1.90	1.49
DS			5.55	2.19	1.49
PH pre-IEEE 693			0.55	0.28	
SA				4.89	3.88

Average PGA Fragility levels (Medians)

The Elephant in the Room


SERA v 9.2 Customer Outage Forecast
Can SERA Reasonably Predict Power Outages?
SERA Forecast vs Actual, 12 M 6+ Earthquakes
Observed Outages (Customers)
1,000,000
100,000
10,000
1,000
100
100
1,000
10,000
100,000
1,000,000
SERA 9.2 Forecast Outages (Customers)
Regression line: nearly a 1:1 slope

Fragility of Overhead Feeders



This reflects 25 years of data collection!

Some data from Ridgecrest 2019

- July 4. M 6.4. 49 incidents. 19,501 customers lose power. CM = 16.1 Million
- July 5. M 7.1. 87 incidents. 17,808 customers lose power. CM = 19.4 Million
- In comparison. Winter storm: 200 Million CM (1+ times per year). High wind event: 500 Million CM (1 time per century). M 7 Earthquake: 1 Billion CM. M 8 Earthquake: 5 Billion CM (?)
- What's acceptable in California?
  - 40 Million to 100 Million CM: customers generally satisfied.
  - 500 MillionCM: some customers angry.
  - 5 Billion: politics takes over, anything can happen.

Date	Time	Crew Size	Crews Needed	Duration Hrs	Man hours	Damage Summary
07/19/2019	13:25:00	4	1	4	16	Wire Stripped to Steel Core
07/06/2019	8:58:00	4	1	8	32	Cross-Arm
07/04/2019	18:31:00	4	1	4	16	Cross-Arm
07/22/2019	10:23:00	4	1	4	16	Cross-Arm
07/06/2019	5:12:00	4	1	8	32	Cross-Arm
07/06/2019	4:09:00	4	1	4	16	Cross-Arm
07/06/2019	12:17:00	4	1	10	40	Transformer / Fire
07/06/2019	2:12:00	4	1	8	32	Leaning Pole / Replaced Pole
07/06/2019	6:13:00	4	1	16	64	Broken Tap
07/07/2019	17:09:00	4	1	6	24	Birdcage / Flashover / Broken Insulator
07/05/2019	13:30:00	1	1	1	1	Pri. Wire Down
07/06/2019	1:30:00	4	1	8	32	Pri. Wire Down
07/06/2019	23:50:00	4	1	4	16	Replace Street Light Pole
07/07/2019	20:01:00	5	1	1	5	Transformer
07/10/2019	7:08:00	4	1	8	32	UG Sec. Damaged
07/07/2019	21:52:00	4	1	6	24	Transformer
07/05/2019	15:36:00	4	1	8	32	UG Sec. Damaged
07/08/2019	11:33:00	4	1	8	32	Broken Insulator / Flashover
07/30/2019	12:25:00	1	1	4	4	Equipment Twisted / Repaired
07/08/2019	12:25:00	4	1	4	16	Sec. Wire Down
07/06/2019	19:10:00	4	4	5	80	Leaning Pole / Repair Pole
07/04/2019	14:45:00	1	1	1	1	Pri. Wire Down/ Cross-Arm
07/05/2019	15:14:00	5	1	8	40	Pri. Wire Down

Remote area. Might be EQ-related

3 Transformer Frames: High W, Low Frequency, High Wire “snapping” forces, High Torsion = high displacement demand on drop wires

Tilted Poles

Birdcaging

Why: high curvature. What causes the high curvature: cable galloping dynamics

Insulators

Why: high conductor forces. If copper wires, wires can break.
If ASCR wires (aluminum with steel core), the conductor is so strong, the insulator breaks.
Or, sometimes the cross arm breaks.

Root cause: no seismic design to determine forces in wires and limit forces to allowable

Street Lights

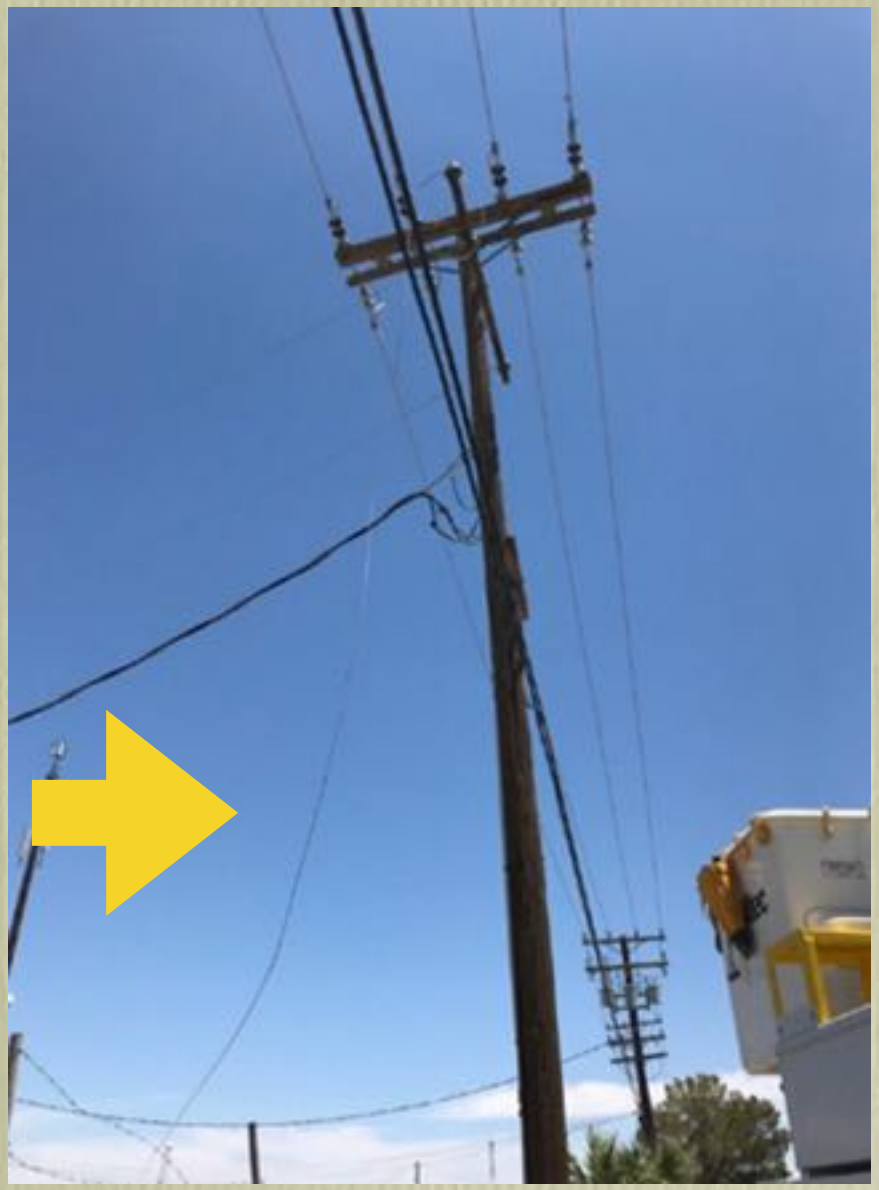
Replaced

Not Replaced

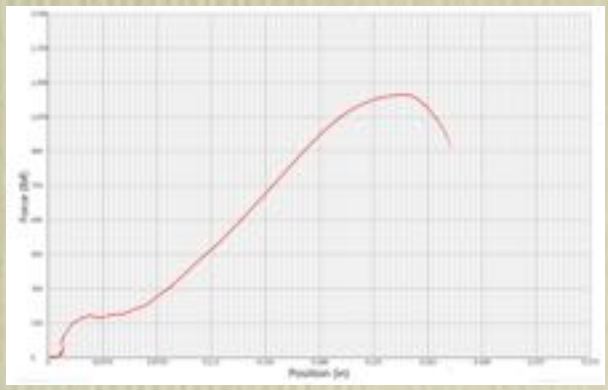
Located < 100 meters away

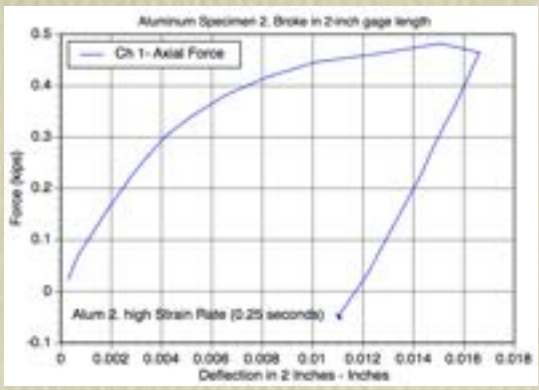
Inertial loading. Why? ShakeMap shows PGA 0.28g constant for both these poles.
Most likley, this was not the case, and PGA (spectra) was >> 0.28g.
(or, did local Dogs weaken these poles?). Corrosion is KING

Wire Down



Wire Test Data





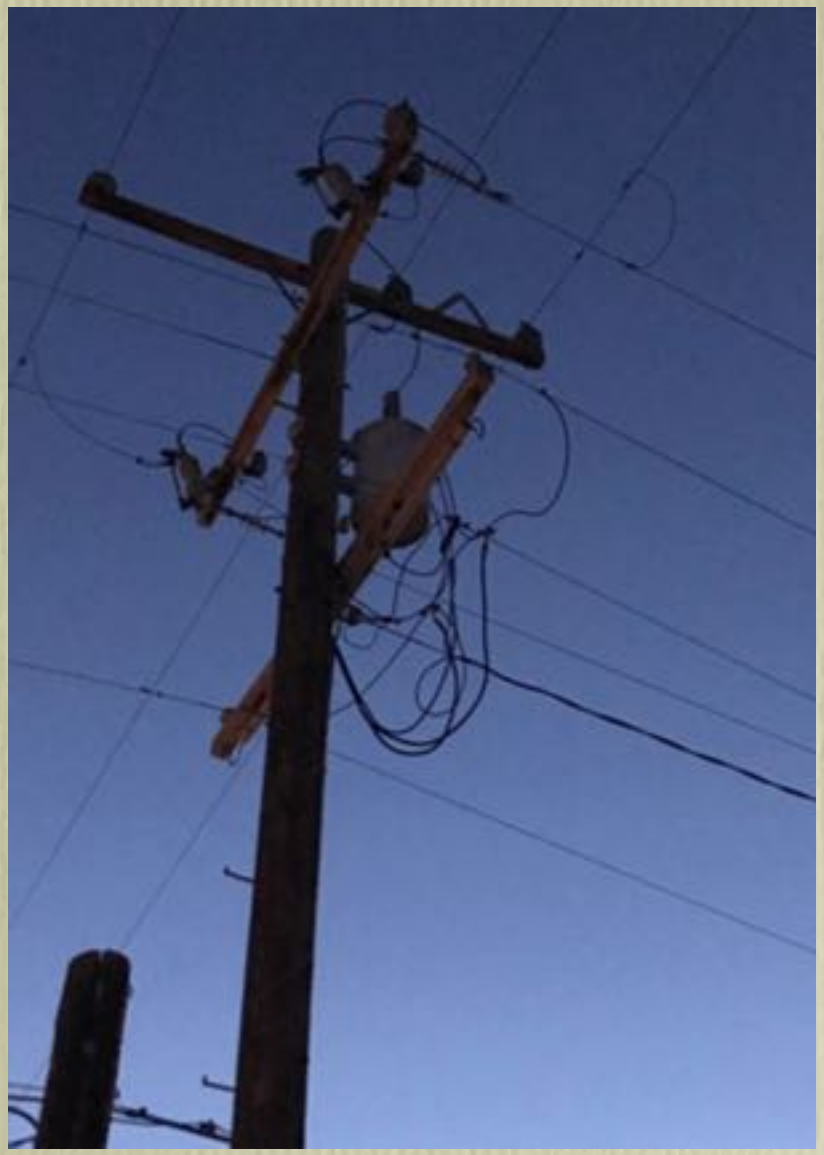
Copper Wires: Break forces around 1,200 pounds. Non-ductile, Strain at failure ~ 2%
Aluminum wires: Non-ductile if using electrical-grade aluminum

Cross Arms

Cross Arms

Older Transformers hooked onto Cross Arms
Not many of these left....

Wrapped Wires



Secondary neutral wrapped around an energized phase leading to burn down.

Cable / Pole Snapping Forces

Trends

- Rate of failures much higher if poles are in liquefied zones
- Drop span poles (lots of sag to produce zero forces under normal conditions) have much higher rates of repairs
- Phase-to-phase causes momentary outages (commonly a few seconds), or opens a breaker (recloser) requiring inspection before re-energizing, or opens a fuse or causes an entanglement / burn down, requiring repair.
- Fragility: PGA, PGV, SA(T=3.0 seconds).

Summary

- SERA - ShakeMap. These tools can predict power outages. All you need is inventory, fragility, hazards.
- Substations. The problem is largely "solved". Some utilities implement. Others are waiting for that 66 million year event
- 475, 975, 2475 years "code-probabilistic". These are actually 3, 4, 7 years "reality" for a large geographic area.
- $300 Billion will reduce power outages by 90%. Maybe SERA - ShakeMap tools can do this "smarter"

Thank you