

APPENDIX C: Fragility Curves Developed by Utilities Working Group

C.1 General Description of Fragility Curves

The opinion-based fragility curves developed by the Utilities Working Group are defined by four parameters: minimum peak ground acceleration for the onset of damage, and PGA at the 16th, 50th and 84th damage percentiles. Parameters for each type of equipment and failure mode are summarized in tables in Section C.2. The curves plotted in Section C.2 were created by combining two Normal distributions: $N(m, \sigma_1)$ for probabilities less than 0.5 and $N(m, \sigma_2)$ for values greater than 0.5. The median (m) of the Normal distribution is the 50th percentile node summarized in the tables. The values of σ_1 and σ_2 are determined by assuming that $m - \sigma_1 = 16$ th percentile and $m + \sigma_2 = 84$ th percentile. Damage probabilities were set to zero for all PGA values less than the assumed minimum needed for the onset of damage.

C.2 Parameters and Plots of Fragility Curves

Table C.1 Fragility Parameters for Transformers

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
TR1	1- phase 230 kV transformer	1 main porcelain gasket leak	0.25	0.25	0.50	0.75
		1 main porcelain break	0.50	0.65	0.85	1.15
		major break in radiator	0.50	0.65	0.85	1.35
		anchorage failure	0.75	0.80	0.95	1.60
		transformer overturn	0.90	1.40	1.50	1.80
TR2	3- phase 230 kV transformer	1 main porcelain gasket leak	0.20	0.20	0.50	0.75
		2 main porcelain gasket leaks	0.20	0.30	0.50	0.85
		3 main porcelain gasket leaks	0.20	0.40	0.50	0.95
		1 main porcelain break	0.20	0.55	0.85	1.15
		2 main porcelain breaks	0.35	0.65	0.85	1.25
		3 main porcelain breaks	0.50	0.75	0.85	1.35
		major break in radiator	0.50	0.65	0.85	1.35
		anchorage failure	0.75	0.80	0.95	1.60
		transformer overturn	0.90	1.15	1.50	2.25
TR3	1- phase 500 kV transformer	1 main porcelain gasket leak	0.10	0.20	0.45	0.70
		1 main porcelain break	0.10	0.50	0.75	1.05
		major break in radiator	0.40	0.55	0.75	1.25
		anchorage failure	0.75	0.80	0.95	1.60
		transformer overturn	0.90	1.40	1.50	1.80
TR4	3- phase 500 kV transformer	1 main porcelain gasket leak	0.10	0.15	0.40	0.65
		2 main porcelain gasket leaks	0.10	0.20	0.40	0.75
		3 main porcelain gasket leaks	0.10	0.30	0.40	0.85
		1 main porcelain break	0.10	0.35	0.65	0.95
		2 main porcelain breaks	0.10	0.45	0.65	1.05
		3 main porcelain breaks	0.10	0.55	0.65	1.15
		major break in radiator	0.40	0.50	0.70	1.20
		anchorage failure	0.75	0.80	0.95	1.60
		transformer overturn	0.90	1.40	1.50	1.80

Figure C.1 Utilities Working Group Fragilities for Single Phase 230 kV Transformers (TR1)

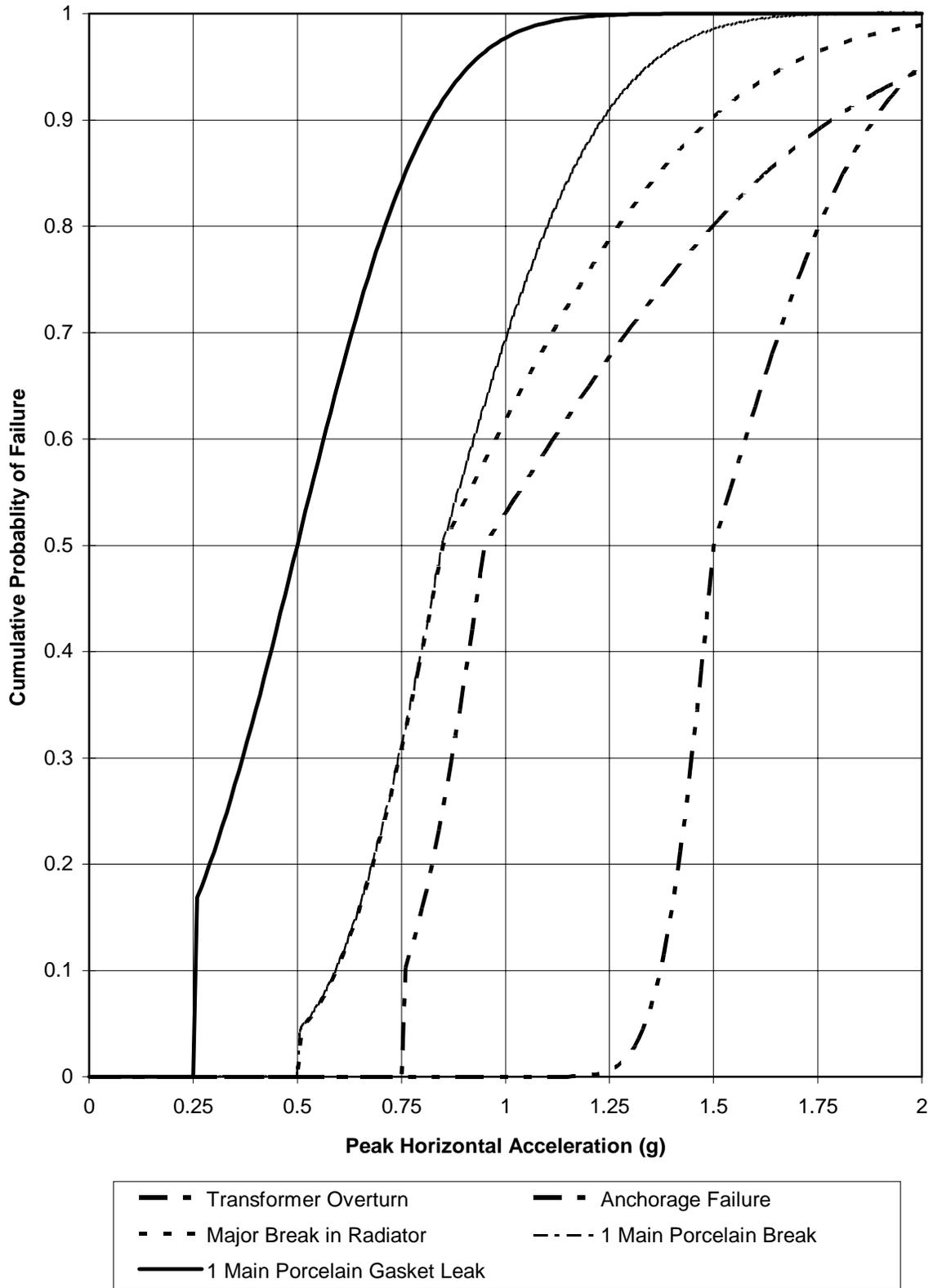


Figure C.2 Utilities Working Group Fragilities for Three Phase 230 kV Transformers (TR2)

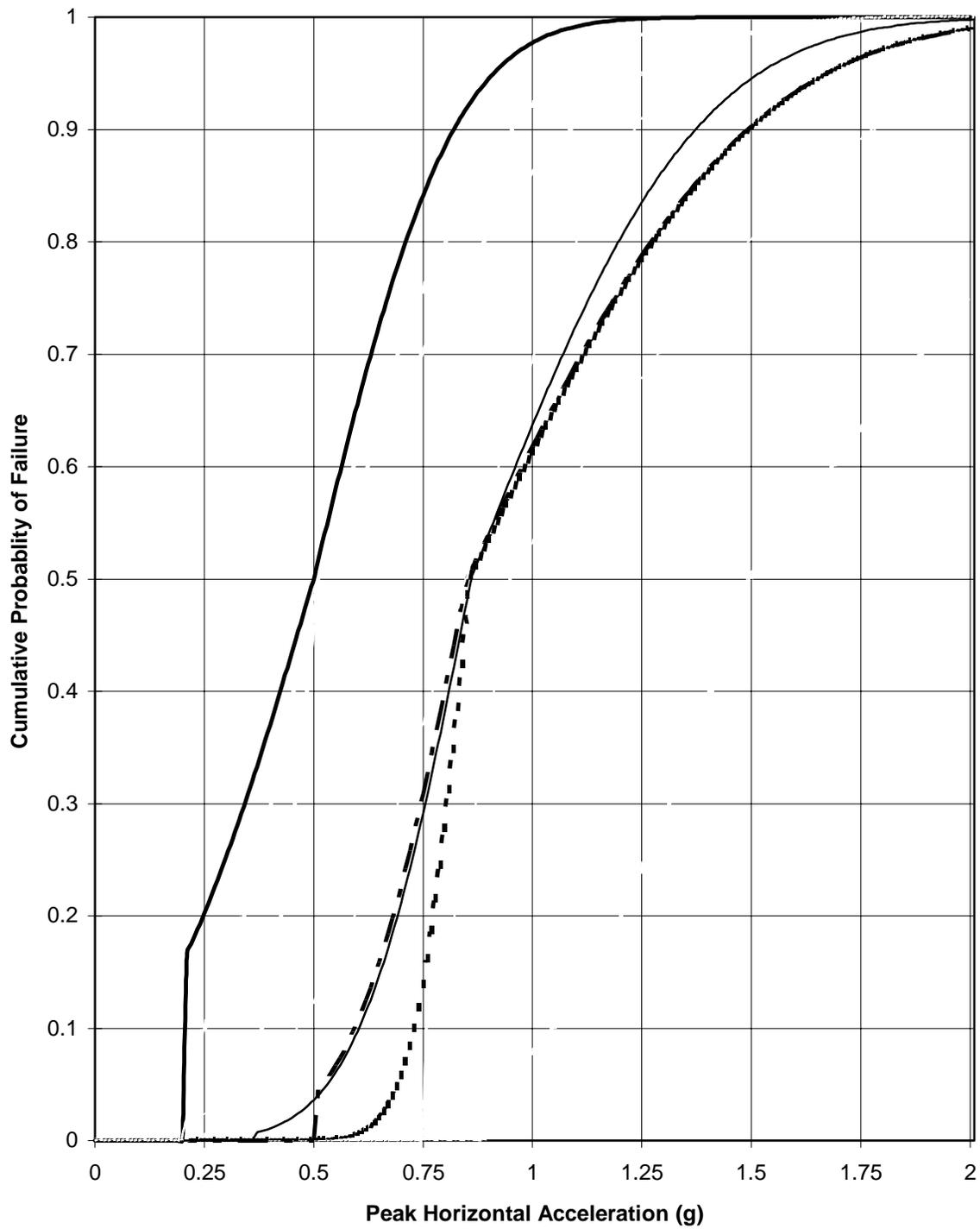


Figure C.3 Utilities Working Group Fragilities for Single Phase 500 kV Transformers (TR3)

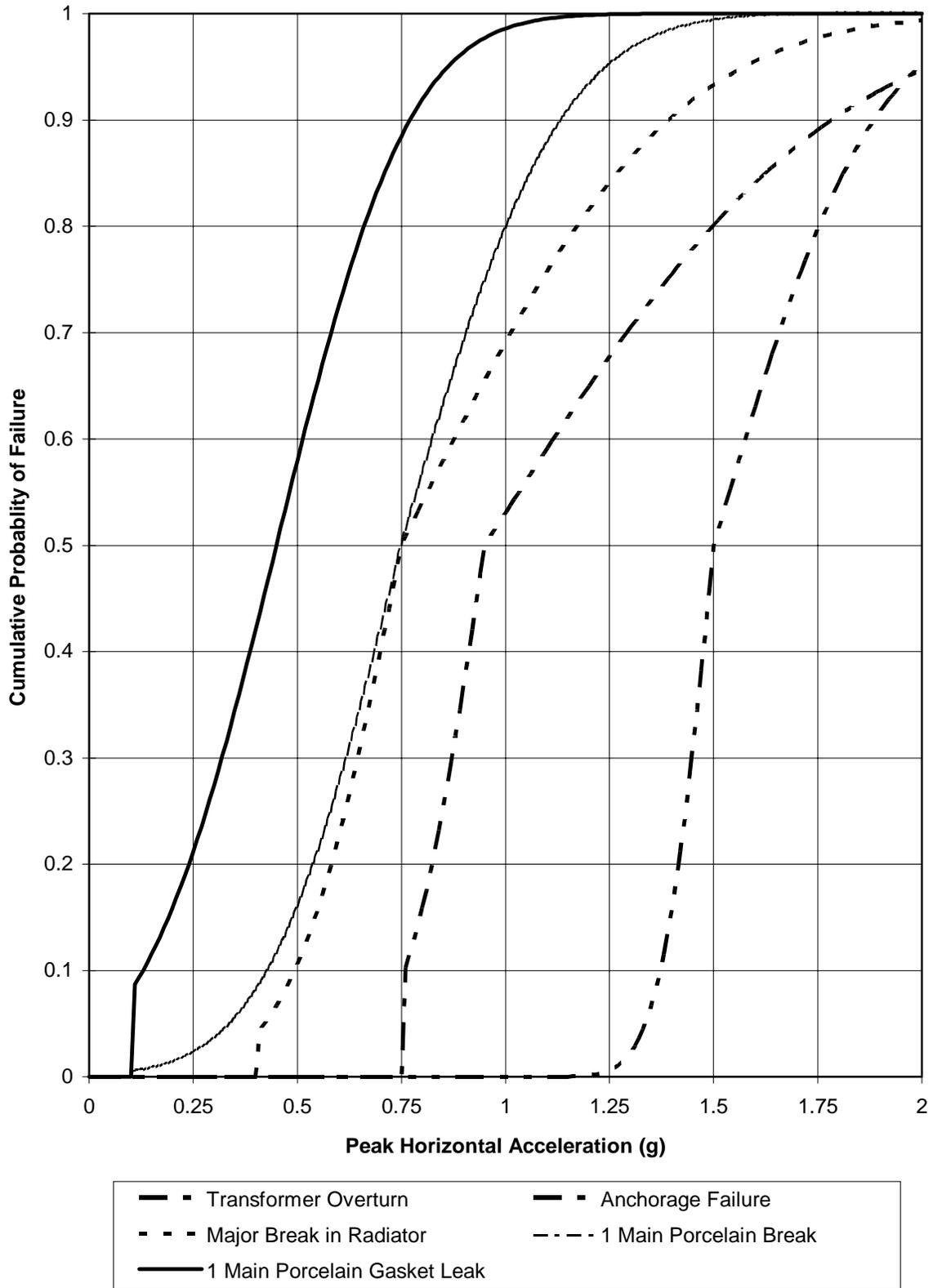


Figure C.4 Utilities Working Group Fragilities for Three Phase 500 kV Transformers (TR4)

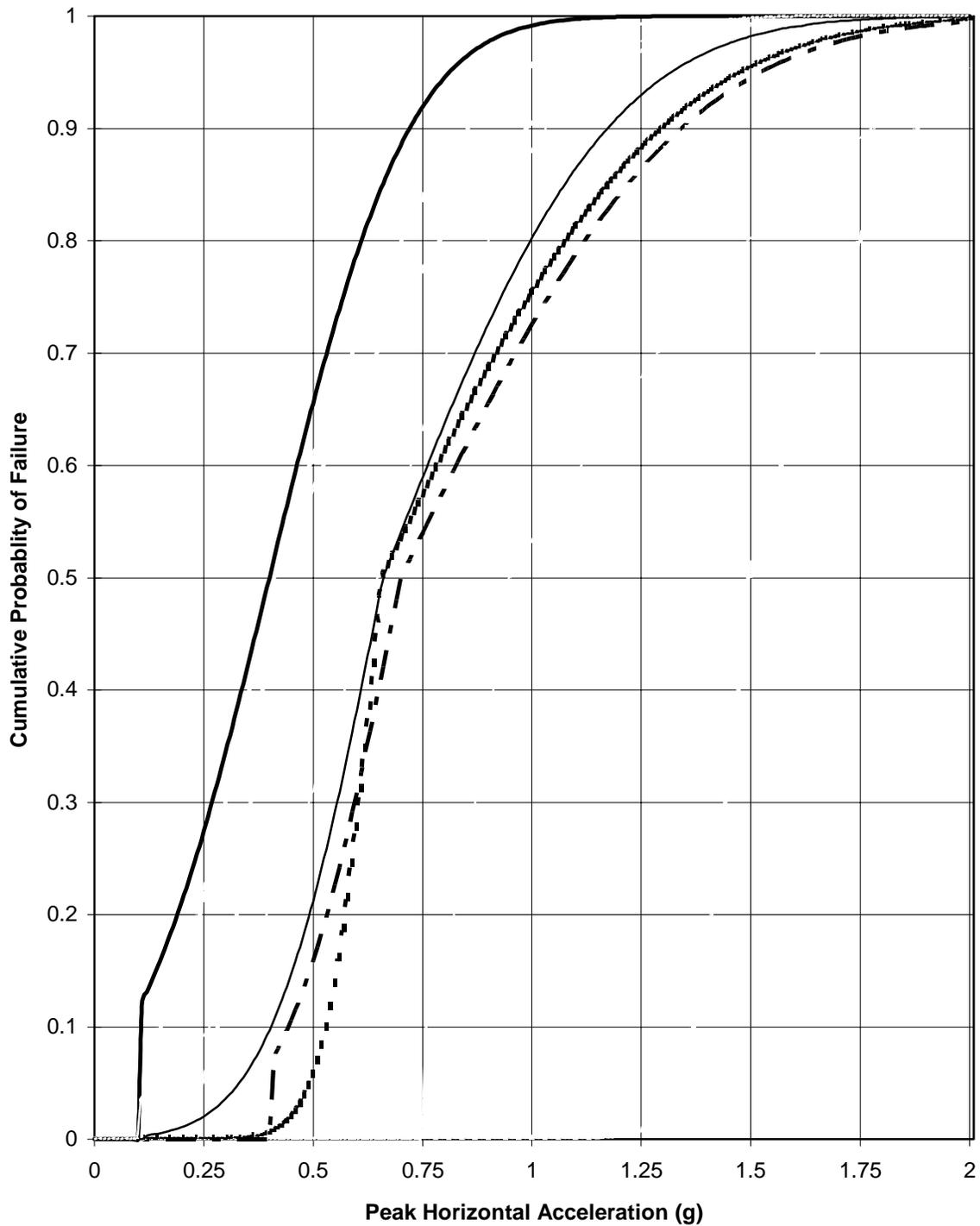


Table C.2 Fragility Parameters for Circuit Breakers

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
CB5	500 kV old Cogenel	collapse of all columns	0.15	0.20	0.30	0.55
CB9	230 kV live tank General Electric ATB4, ATB5, ATB6	column base gasket leak	0.08	0.10	0.25	0.35
		1 porcelain column fails	0.10	0.15	0.30	0.45
		2 porcelain columns fail	0.10	0.20	0.35	0.50
CB14	230 kV live tank General Electric ATB7	1 porcelain column fails	0.04	0.08	0.15	0.30
		2 porcelain columns fail	0.04	0.13	0.20	0.40
CB15	500 kV live tank General Electric ATB	column base gasket leak	0.10	0.15	0.25	0.35
		1 porcelain column fails	0.10	0.15	0.30	0.50
		2 porcelain columns fail	0.10	0.15	0.35	0.55
CB15a	500 kV live tank other	column base gasket leak	0.10	0.15	0.25	0.35
		1 porcelain column fails	0.10	0.15	0.30	0.50
		2 porcelain columns fail	0.10	0.15	0.35	0.55
CB20	230 kV dead tank SF6	1 porcelain column fails	0.40	1.00	1.20	1.50
		2 porcelain columns fail	0.40	1.00	1.20	1.60
CB20a	230 kV dead tank oil	anchorage fails	0.10	0.20	0.50	1.00
		1 porcelain column fails	0.40	1.00	1.20	1.50
		2 porcelain columns fail	0.40	1.00	1.20	1.60
CB57	230 kV modern dead tank	1 porcelain column fails	0.40	0.45	0.65	0.85
		2 porcelain columns fail	0.40	0.50	0.70	1.10
CB72	500 kV live tank Westinghouse SF6	head porcelain damage	0.15	0.25	0.35	0.50
		1 porcelain column fails	0.15	0.15	0.30	0.45
		2 porcelain columns fail	0.15	0.25	0.35	0.45
		3 porcelain columns fail	0.15	0.30	0.40	0.50
CB73	500 kV live tank puffer	1 porcelain column fails	0.40	1.00	1.20	1.50
		2 porcelain columns fail	0.40	1.00	1.20	1.60
CB77	500 kV dead tank SF6	1 porcelain column fails	0.40	0.80	1.00	1.30
		2 porcelain columns fail	0.40	0.80	1.00	1.40

Figure C.5 Utilities Working Group Fragilities for 500 kV Old Cogenel Circuit Breakers (CB5)

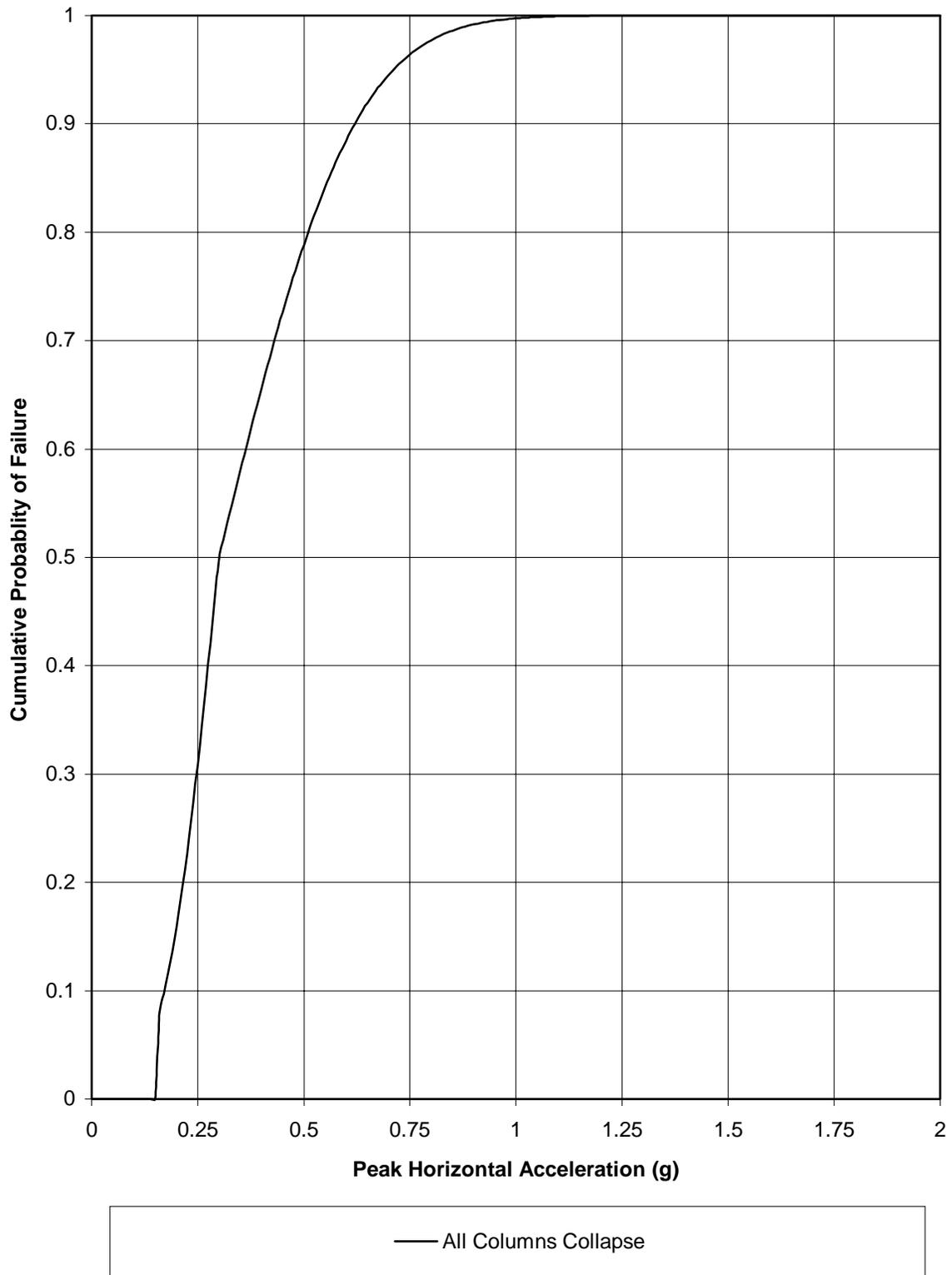


Figure C.6 Utilities Working Group Fragilities for 230 kV Live Tank General Electric ATB4, ATB5, ATB6 (CB9)

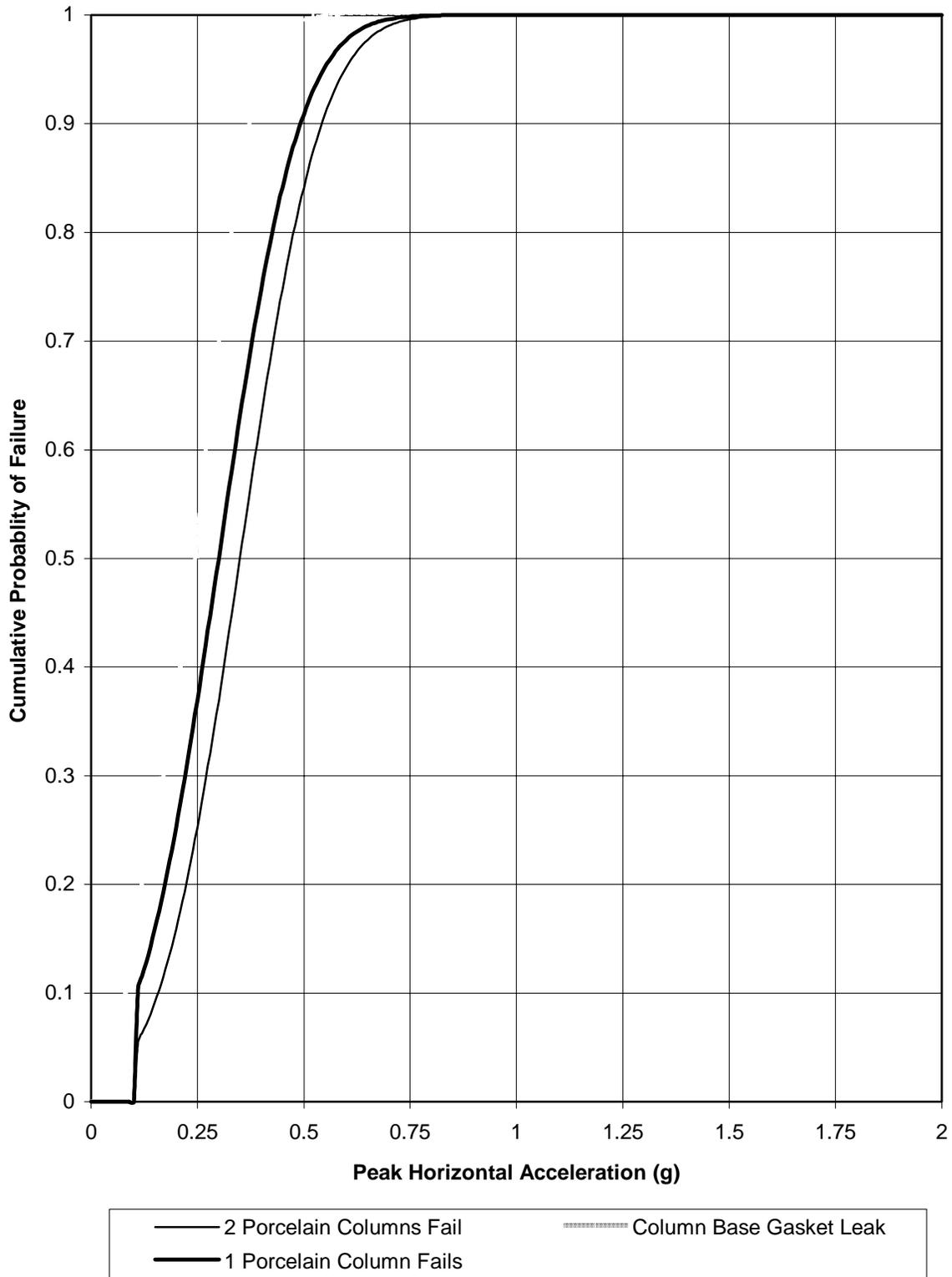


Figure C.7 Utilities Working Group Fragilities for 230 kV Live Tank General Electric ATB7 (CB14)

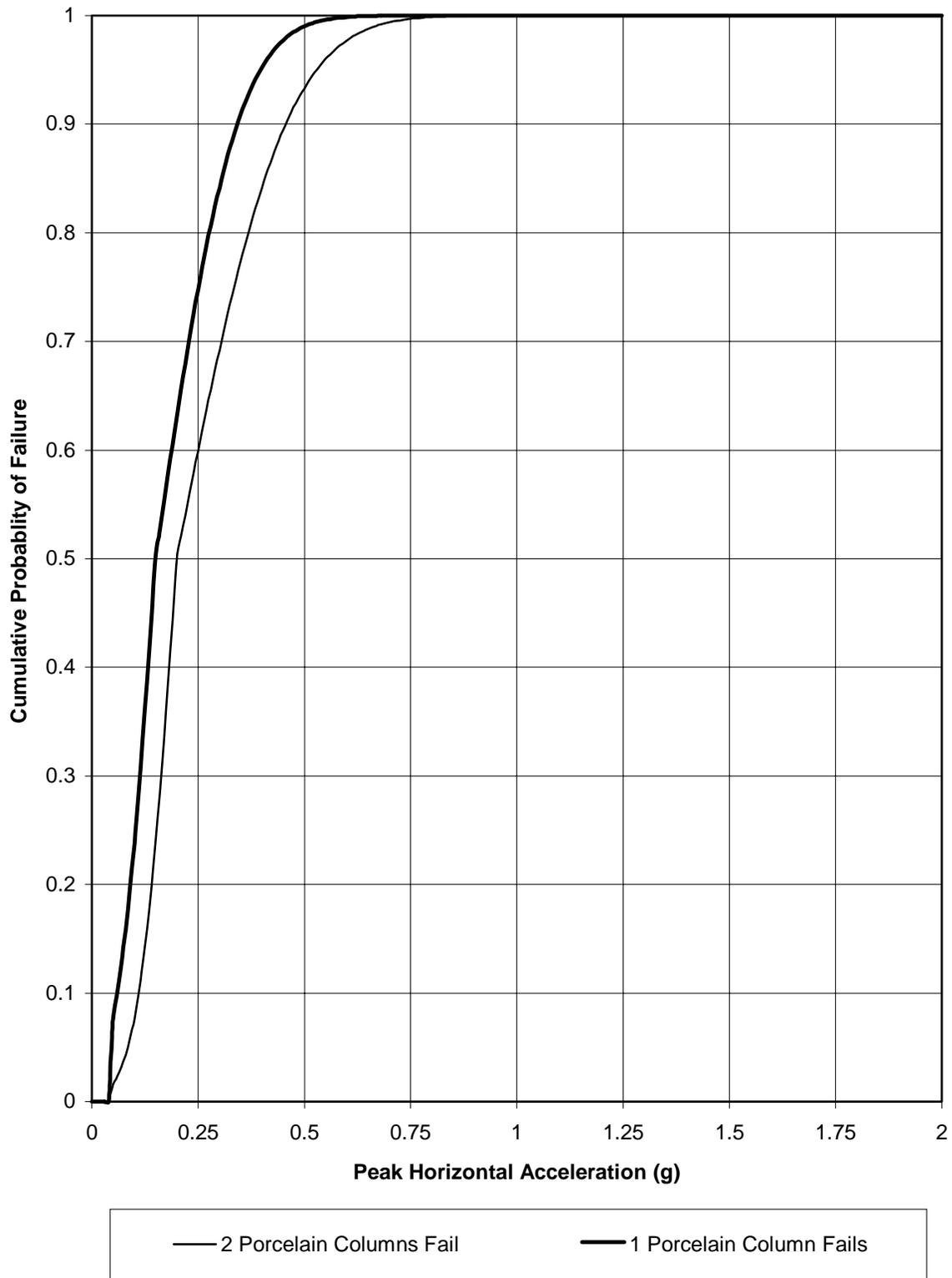


Figure C.8 Utilities Working Group Fragilities for 500 kV Live Tank General Electric ATB (CB15) and Other 500 kV Live Tank (CB15a) Circuit Breakers

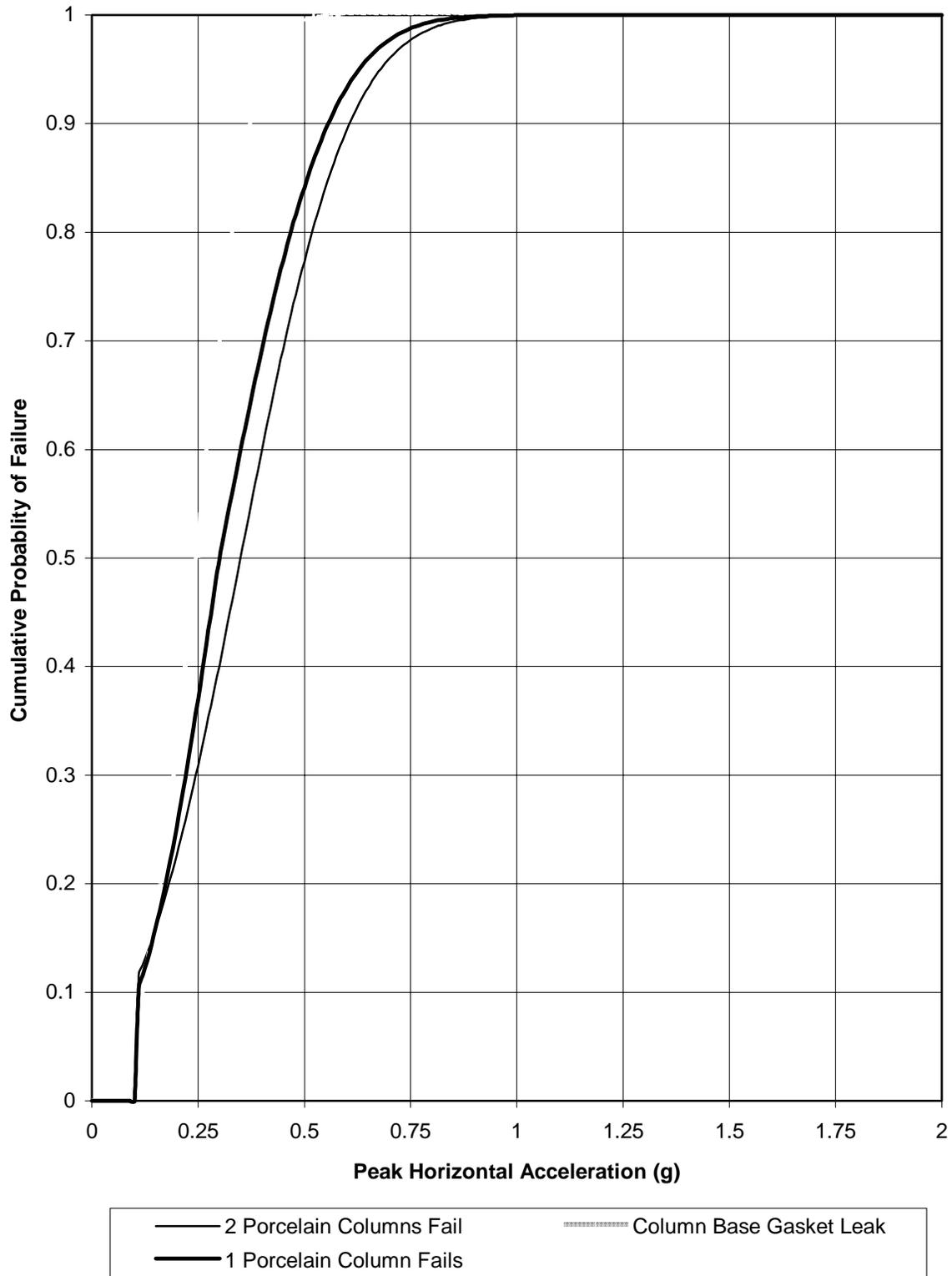


Figure C.9 Utilities Working Group Fragilities for 230 kV Dead Tank SF6 Circuit Breakers (CB20)

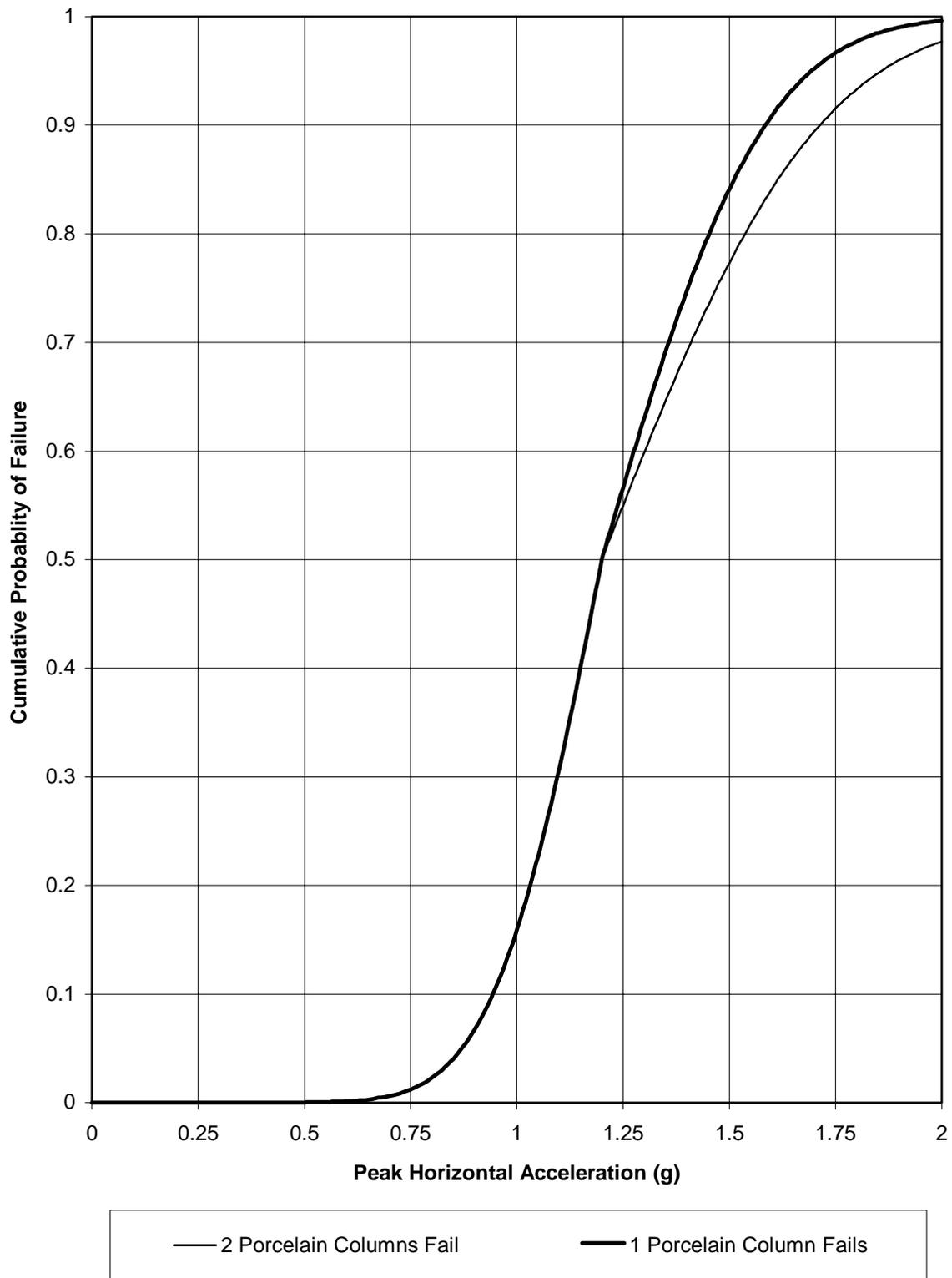


Figure C.10 Utilities Working Group Fragilities for 230 kV Dead Tank Oil Circuit Breakers (CB20a)

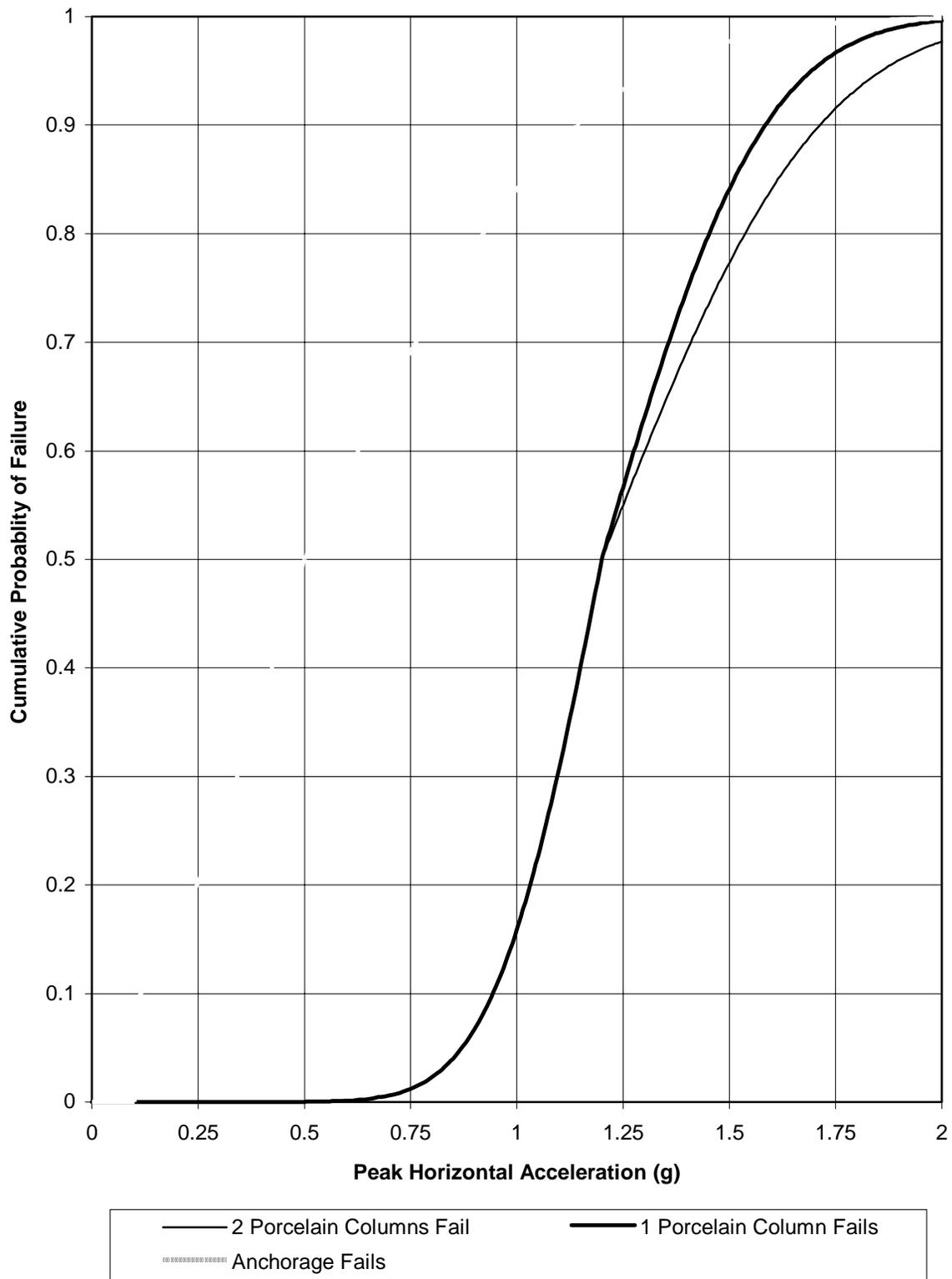


Figure C.11 Utilities Working Group Fragilities for 230 kV Modern Live Tank Circuit Breakers (CB57)

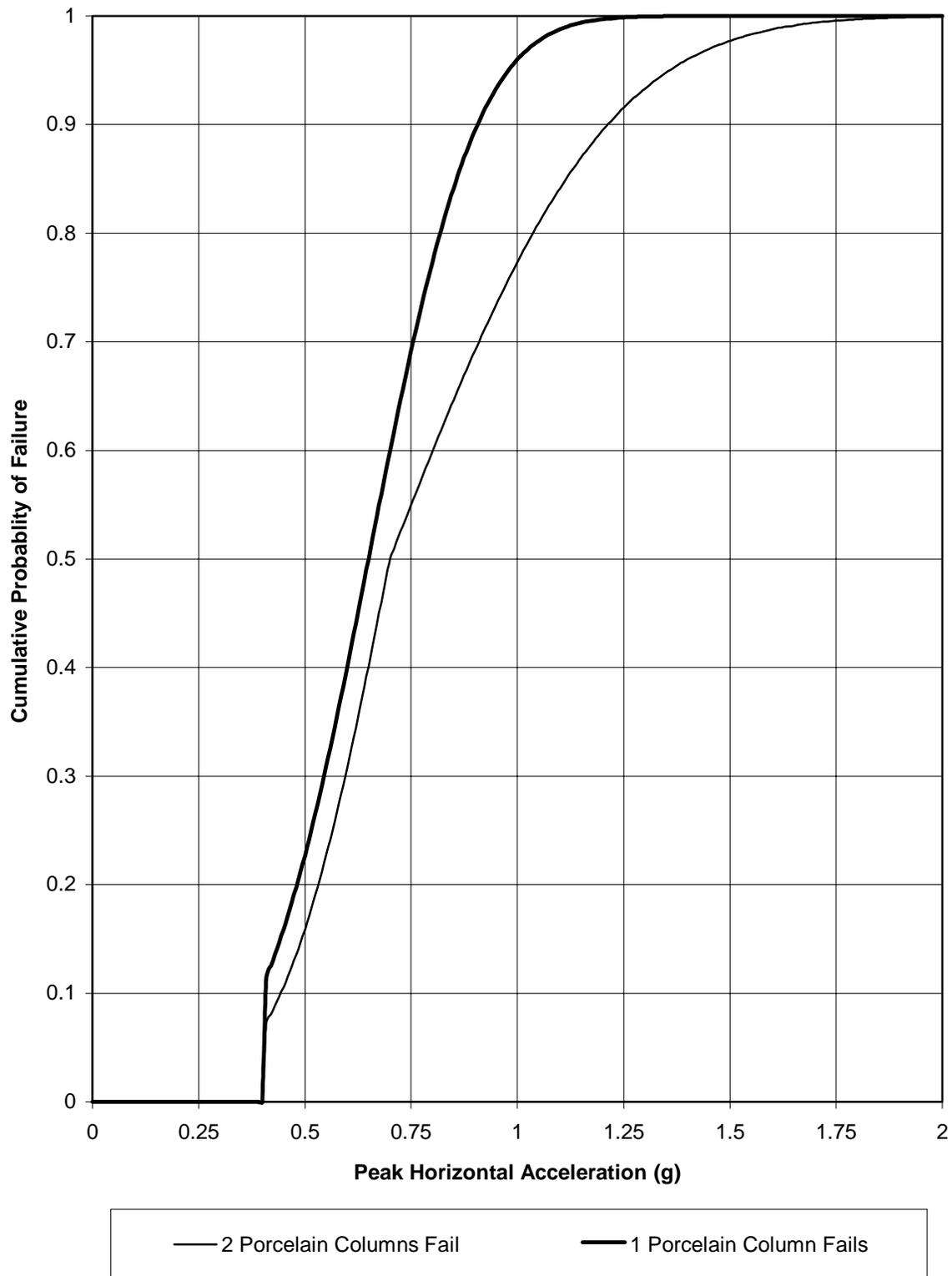


Figure C.12 Utilities Working Group Fragilities for 500 kV Live Tank Westinghouse SF6 Circuit Breakers (CB72)

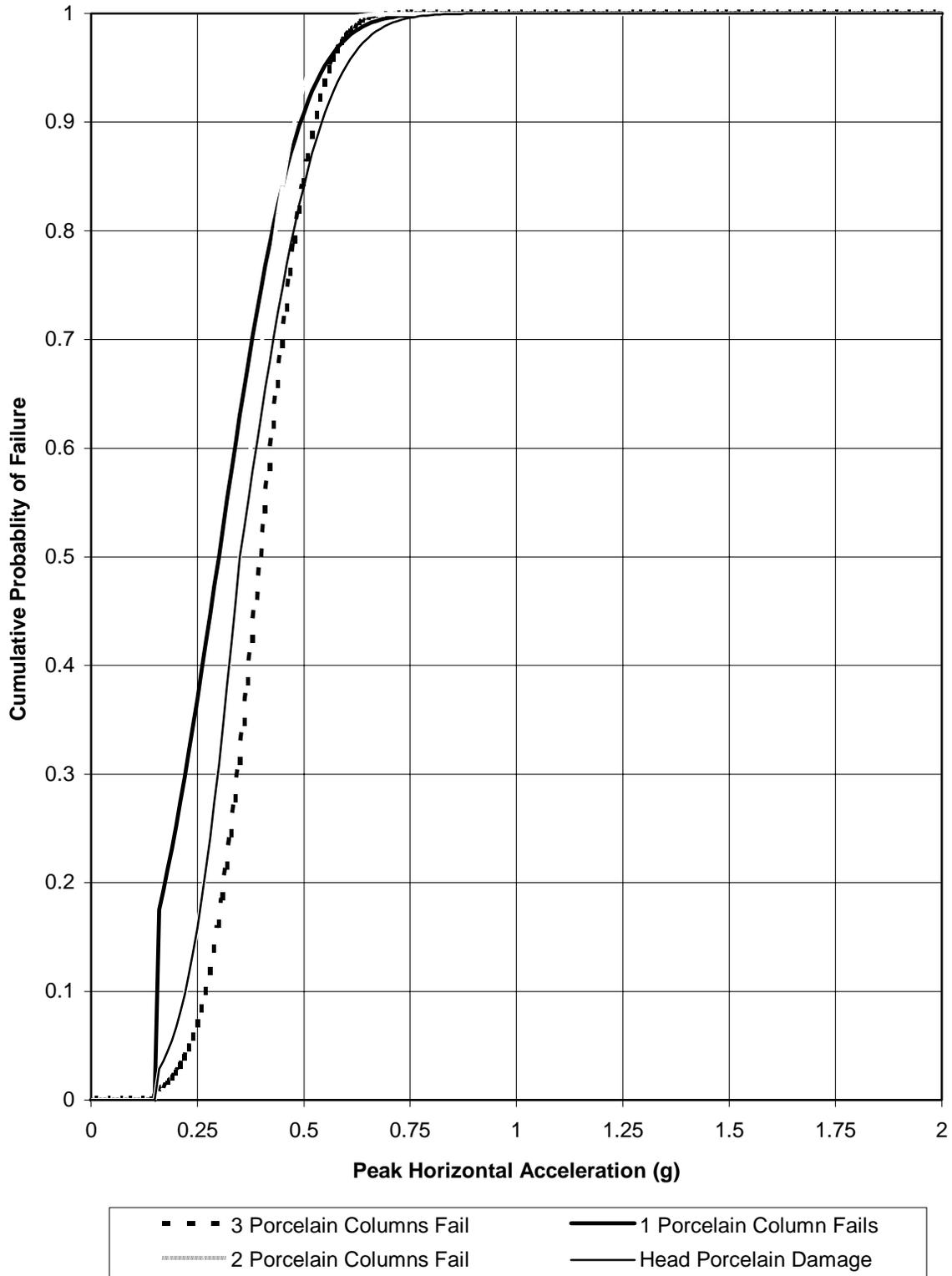


Figure C.13 Utilities Working Group Fragilities for 500 kV Live Tank Puffer Circuit Breakers (CB73)

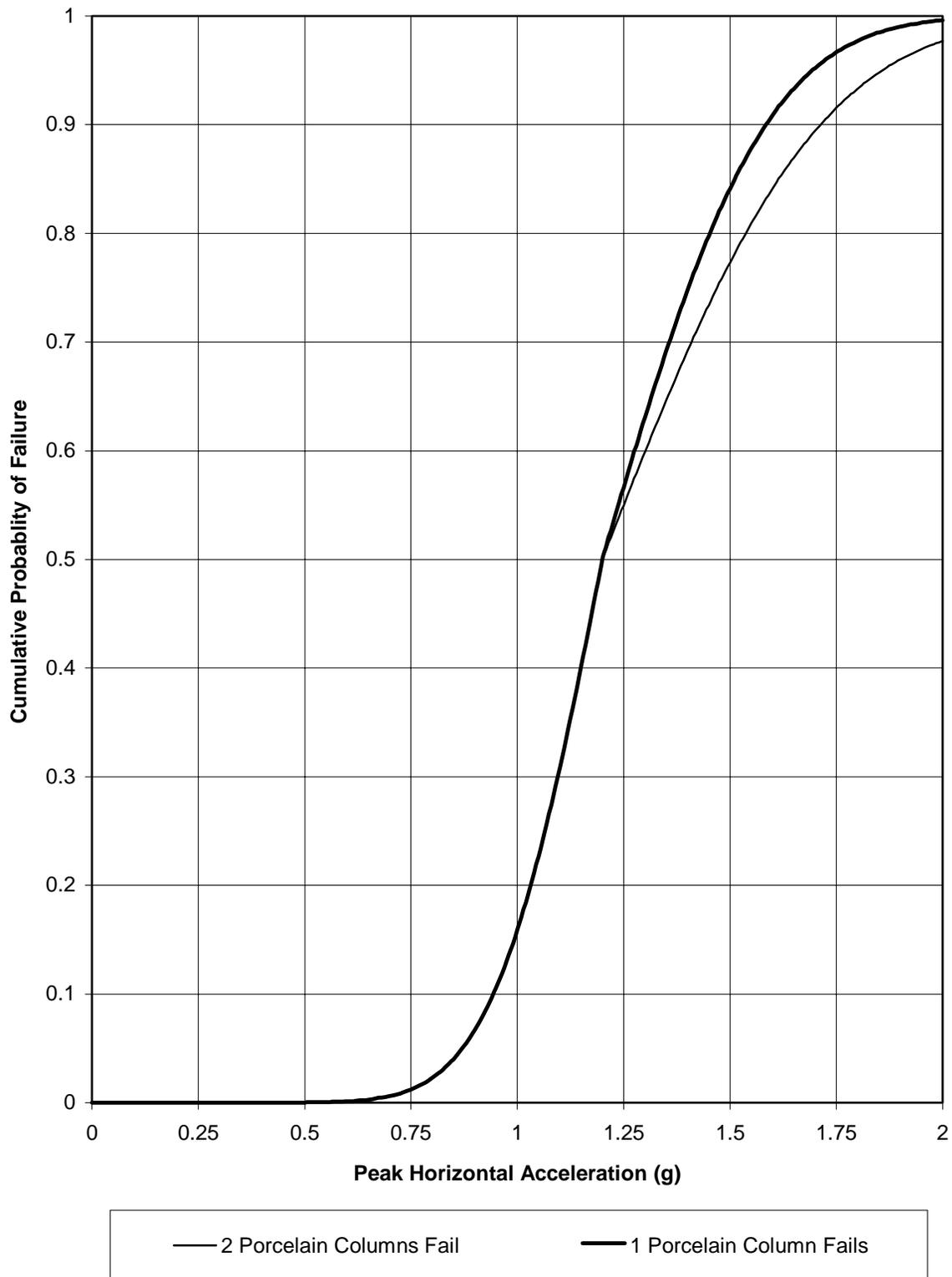


Figure C.14 Utilities Working Group Fragilities for 500 kV Dead Tank SF6 Circuit Breakers (CB77)

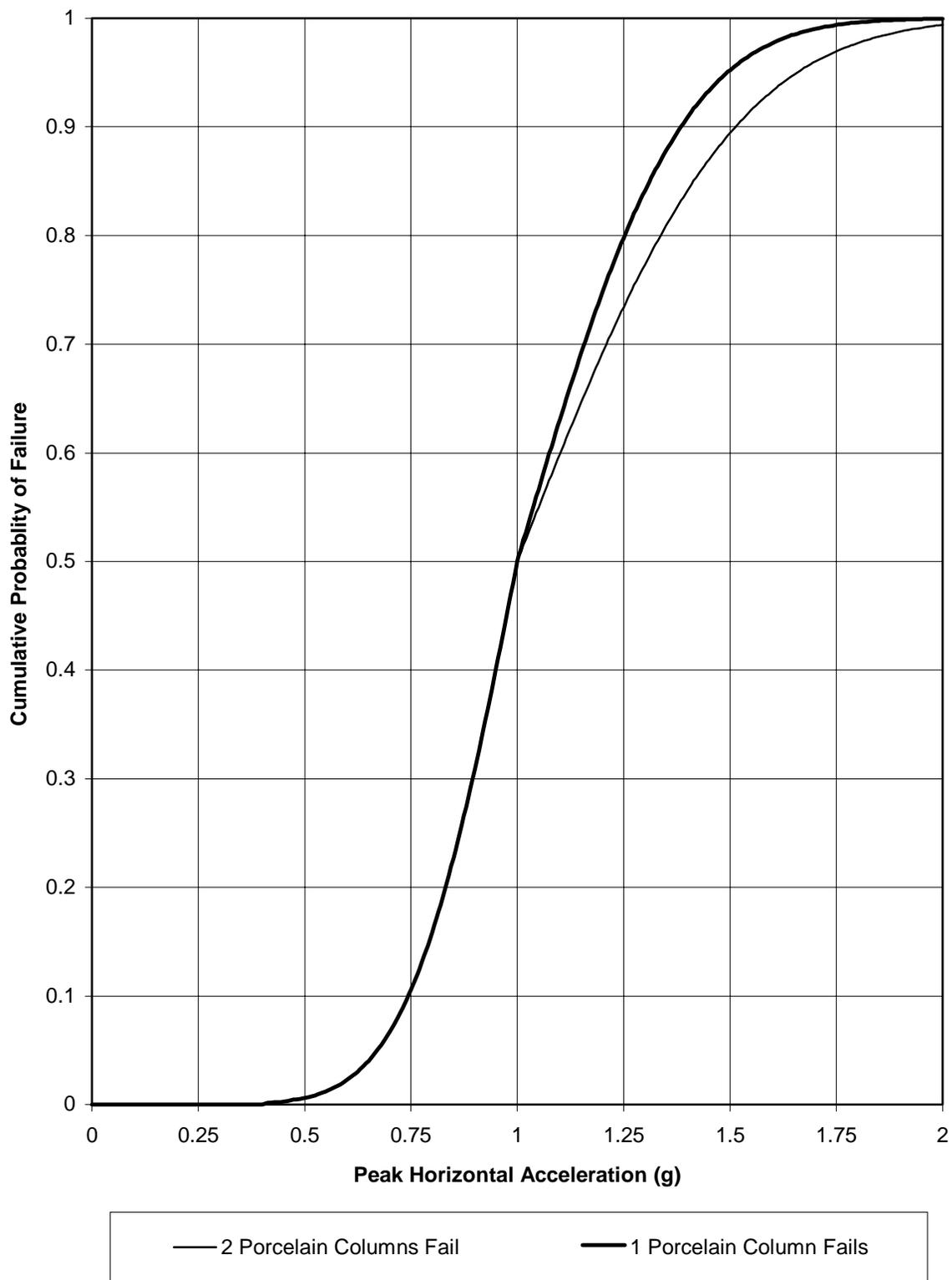


Table C.3 Fragility Parameters for Disconnect Switches

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
DS1	500 kV vertical switch	misaligned contacts	0.20	0.25	0.40	0.55
		porcelain column fails	0.20	0.30	0.40	0.60
DS2	230 kV vertical switch	misaligned contacts	0.20	0.40	0.60	0.80
		broken porcelain	0.30	0.50	0.70	0.90
DS3	230 kV horizontal switch	misaligned contacts	0.20	0.30	0.50	0.70
		broken porcelain	0.30	0.50	0.70	0.90

Figure C.15 Utilities Working Group Fragilities for 500 kV Vertical Disconnect Switches (DS1)

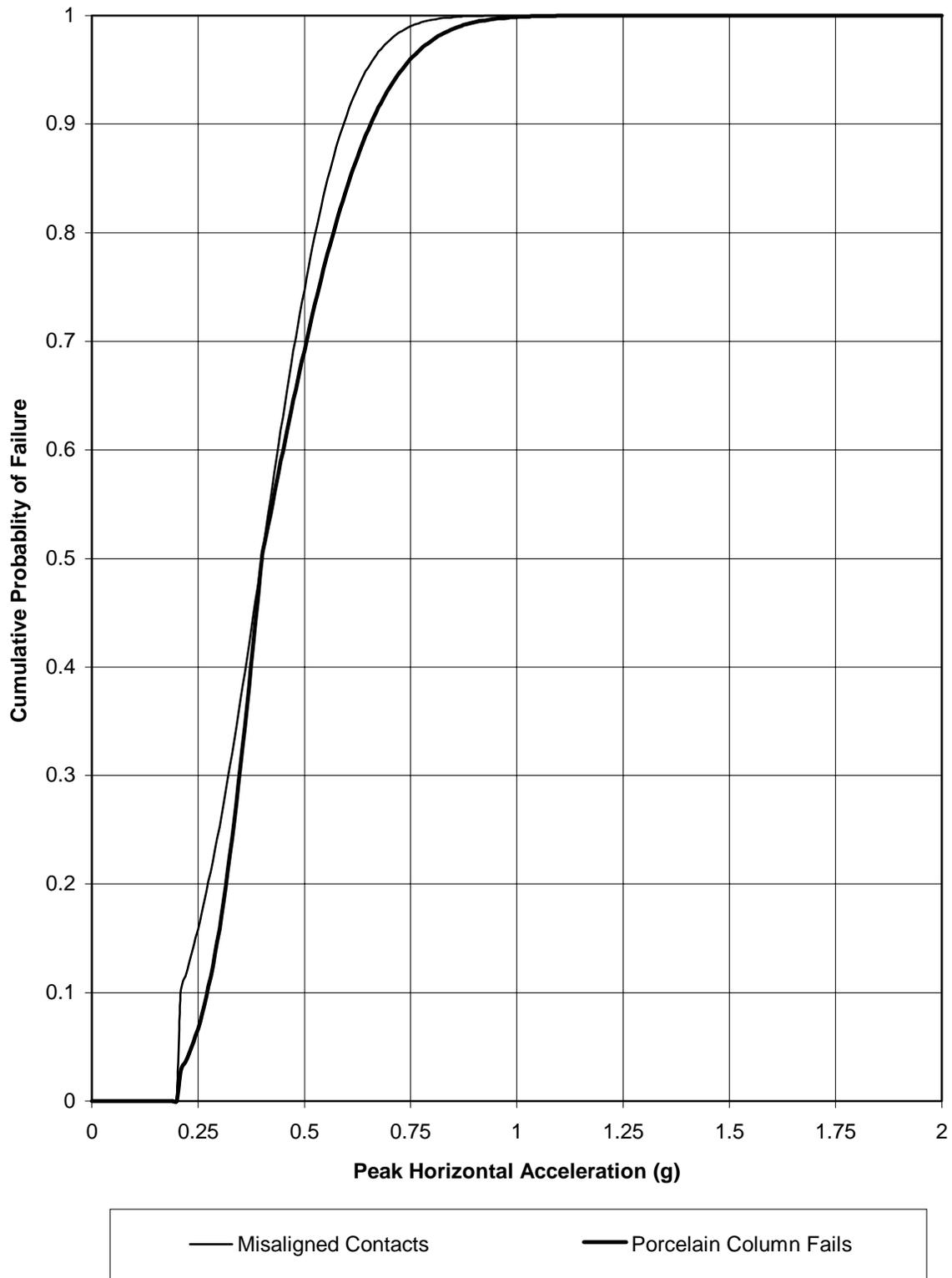


Figure C.16 Utilities Working Group Fragilities for 230 kV Vertical Disconnect Switches (DS2)

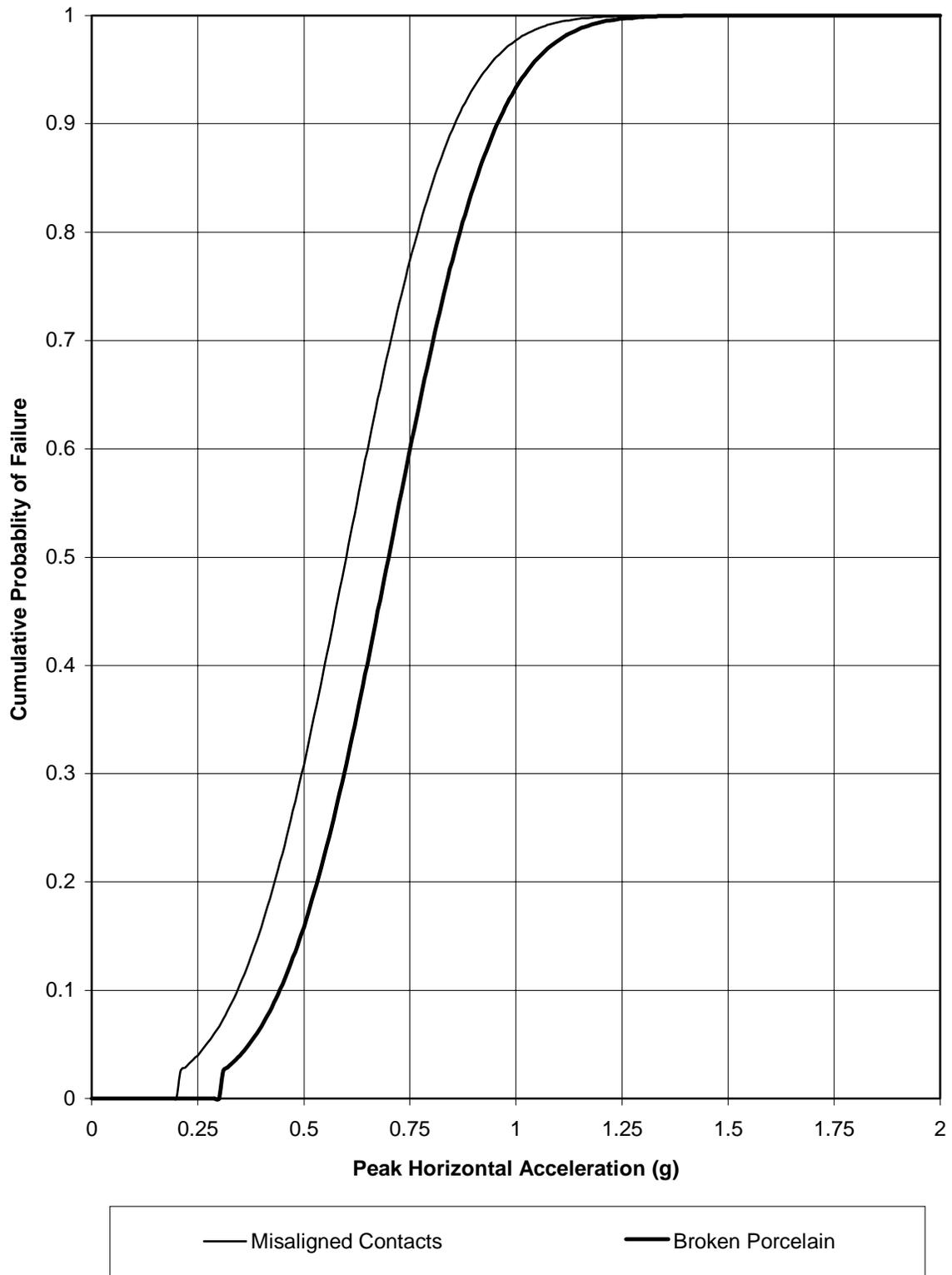


Figure C.17 Utilities Working Group Fragilities for 230 kV Horizontal Disconnect Switches (DS3)

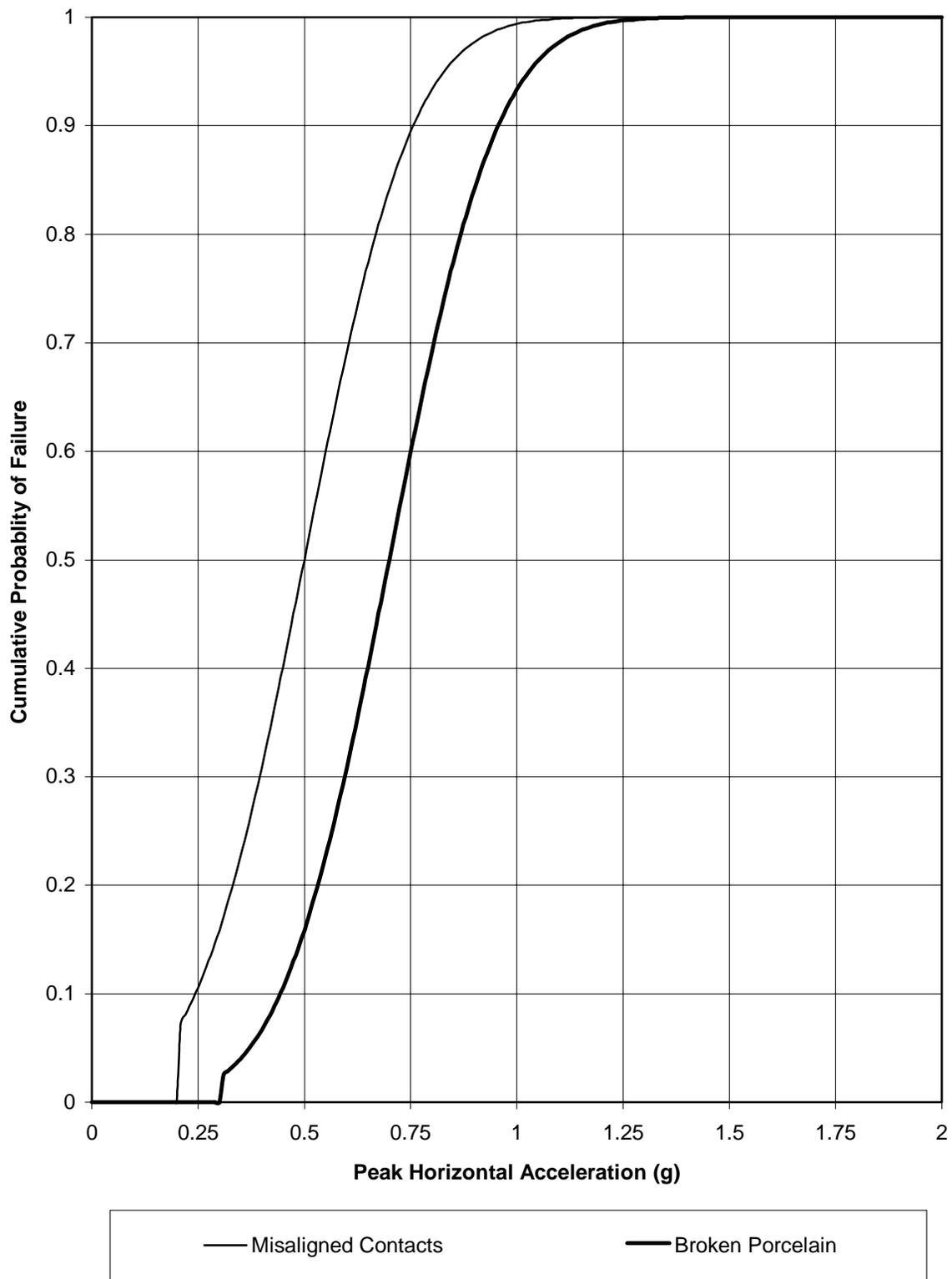


Table C.4 Fragility Parameters for Lightning Arresters

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
LA1	230 kV low seismic design	failure of porcelain column	0.15	0.35	0.55	0.75
LA2	230 kV medium seismic design	failure of porcelain column	0.15	0.45	0.65	0.85
LA3	230 kV high seismic design	failure of porcelain column	0.15	0.55	0.75	0.95
LA4	230 kV composite column	failure of composite column	0.15	0.65	0.85	1.05
LA5	500 kV low seismic design	failure of porcelain column	0.10	0.15	0.25	0.50
LA6	500 kV medium seismic design	failure of porcelain column	0.10	0.25	0.35	0.60
LA7	500 kV high seismic design	failure of porcelain column	0.10	0.35	0.45	0.70
LA8	500 kV composite column	failure of composite column	0.10	0.45	0.55	0.80

Figure C.18 Utilities Working Group Fragilities for 230 kV Lightning Arresters (LA1, LA2, LA3, LA4)

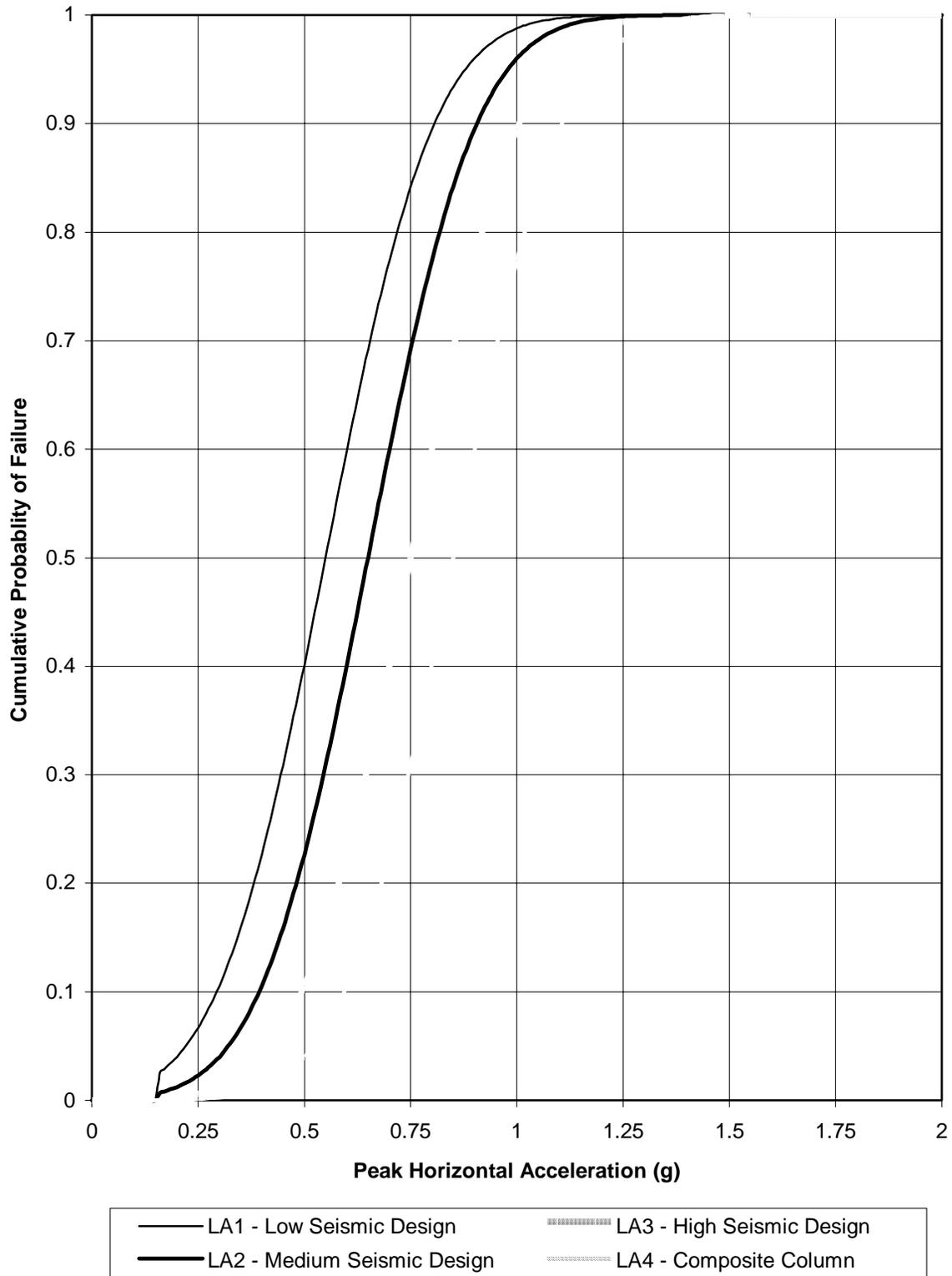


Figure C.19 Utilities Working Group Fragilities for 500 kV Lightning Arresters (LA5, LA6, LA7, LA8)

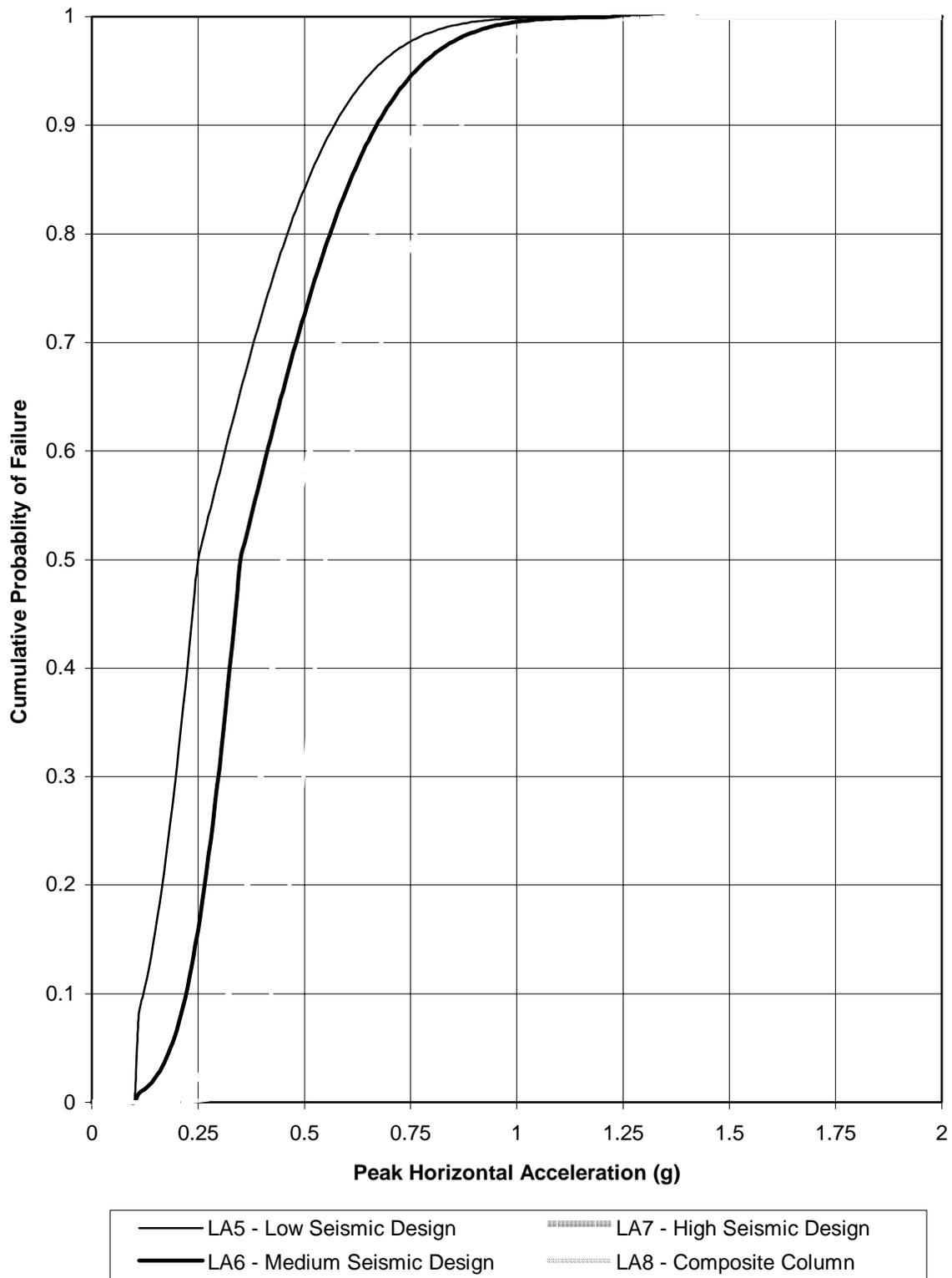


Table C.5 Fragility Parameters for Current Transformers

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
CT1	230 kV low seismic design	failure of porcelain column	0.25	0.20	0.40	0.80
CT2	230 kV medium seismic design	failure of porcelain column	0.25	0.30	0.50	0.90
CT3	230 kV high seismic design	failure of porcelain column	0.25	0.40	0.60	1.00
CT4	230 kV composite column	failure of composite column	0.25	0.60	0.80	1.20
CT5	500 kV low seismic design	failure of porcelain column	0.25	0.20	0.30	0.60
CT6	500 kV medium seismic design	failure of porcelain column	0.25	0.30	0.45	0.65
CT7	500 kV high seismic design	failure of porcelain column	0.25	0.35	0.50	0.70
CT8	500 kV composite column	failure of composite column	0.25	0.50	0.70	0.90

Figure C.20 Utilities Working Group Fragilities for 230 kV Current Transformers (CT1, CT2, CT3, CT4)

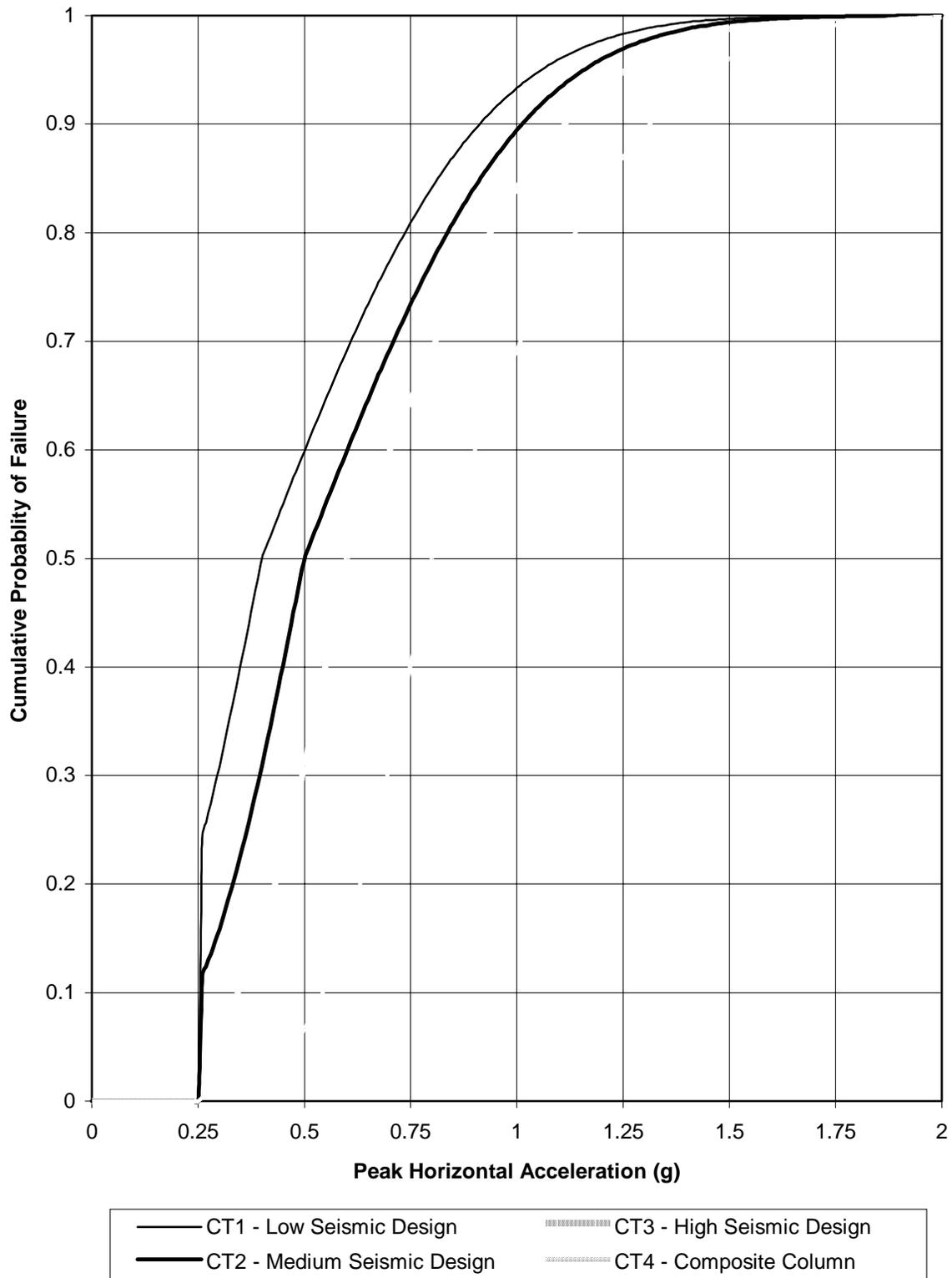


Figure C.21 Utilities Working Group Fragilities for 500 kV Current Transformers (CT5, CT6, CT7, CT8)

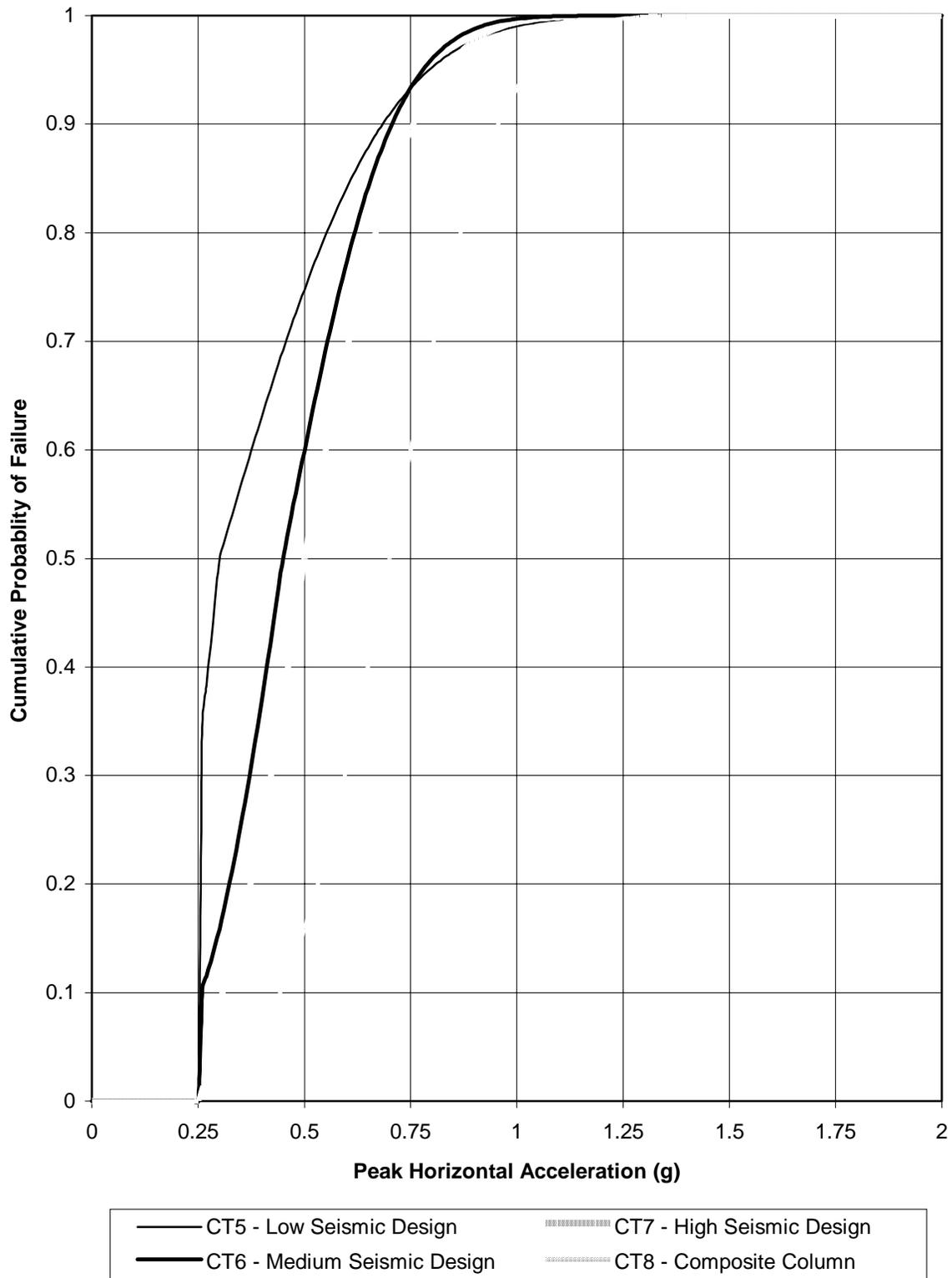


Table C.6 Fragility Parameters for Coupling Capacitor Voltage Transformers

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
CC1	230 kV low seismic design	failure of porcelain column	0.25	.020	0.35	0.55
CC2	230 kV medium seismic design	failure of porcelain column	0.25	0.30	0.45	0.65
CC3	230 kV high seismic design	failure of porcelain column	0.25	0.40	0.55	0.75
CC4	230 kV composite column	failure of composite column	0.25	0.60	0.75	0.95
CC5	500 kV low seismic design	failure of porcelain column	0.25	0.10	0.25	0.45
CC6	500 kV medium seismic design	failure of porcelain column	0.25	0.20	0.35	0.55
CC7	500 kV high seismic design	failure of porcelain column	0.25	0.35	0.50	0.70
CC8	500 kV composite column	failure of composite column	0.25	0.60	0.75	0.95

Figure C.22 Utilities Working Group Fragilities for 230 kV Coupling Capacitor Voltage Transformers (CC1, CC2, CC3, CC4)

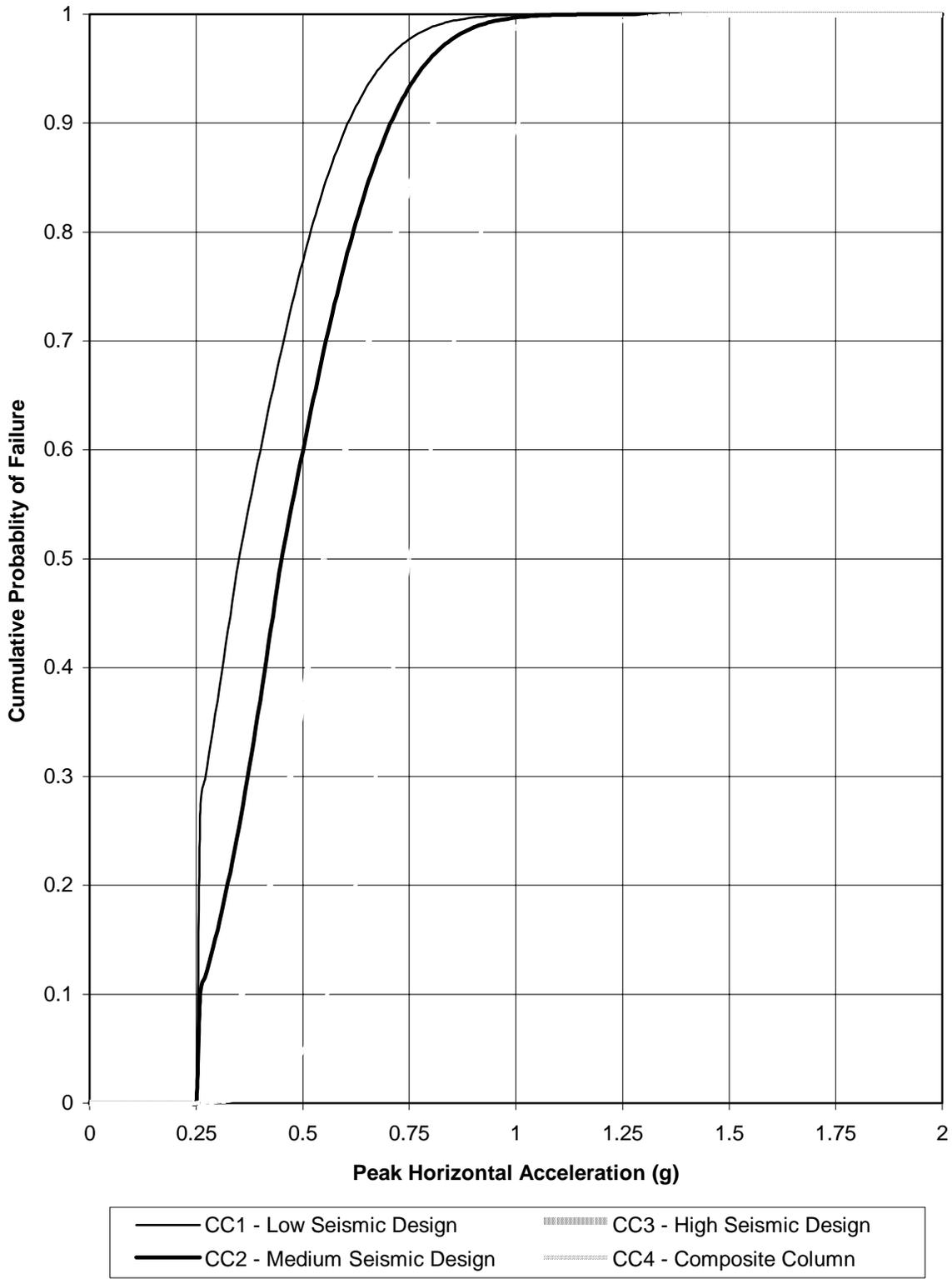


Figure C.23 Utilities Working Group Fragilities for 500 kV Coupling Capacitor Voltage Transformers (CC5, CC6, CC7, CC8)

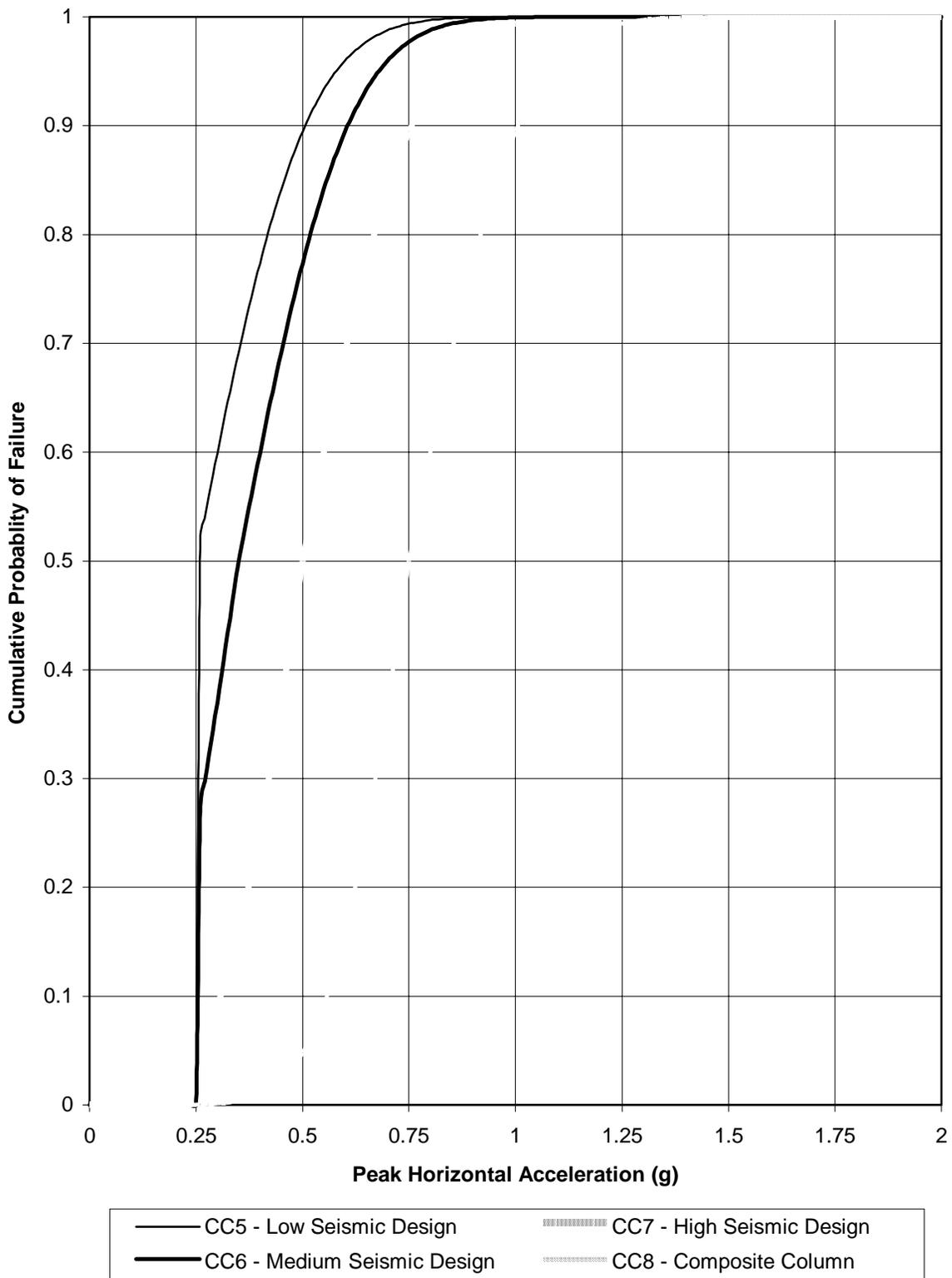


Table C.7 Fragility Parameters for Potential Transformers

UWG Class	Equipment Description	Failure Mode	Fragility Nodes			
			Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
PT1	230 kV low seismic design	failure of porcelain column	0.25	.025	0.40	0.60
PT2	230 kV medium seismic design	failure of porcelain column	0.25	0.35	0.50	0.70
PT3	230 kV high seismic design	failure of porcelain column	0.25	0.45	0.60	0.80
PT4	230 kV composite column	failure of composite column	0.25	0.65	0.80	1.00
PT5	500 kV low seismic design	failure of porcelain column	0.25	0.15	0.30	0.50
PT6	500 kV medium seismic design	failure of porcelain column	0.25	0.25	0.40	0.60
PT7	500 kV high seismic design	failure of porcelain column	0.25	0.35	0.50	0.70
PT8	500 kV composite column	failure of composite column	0.25	0.55	0.70	0.90

Figure C.24 Utilities Working Group Fragilities for 230 kV Potential Transformers (PT1, PT2, PT3, PT4)

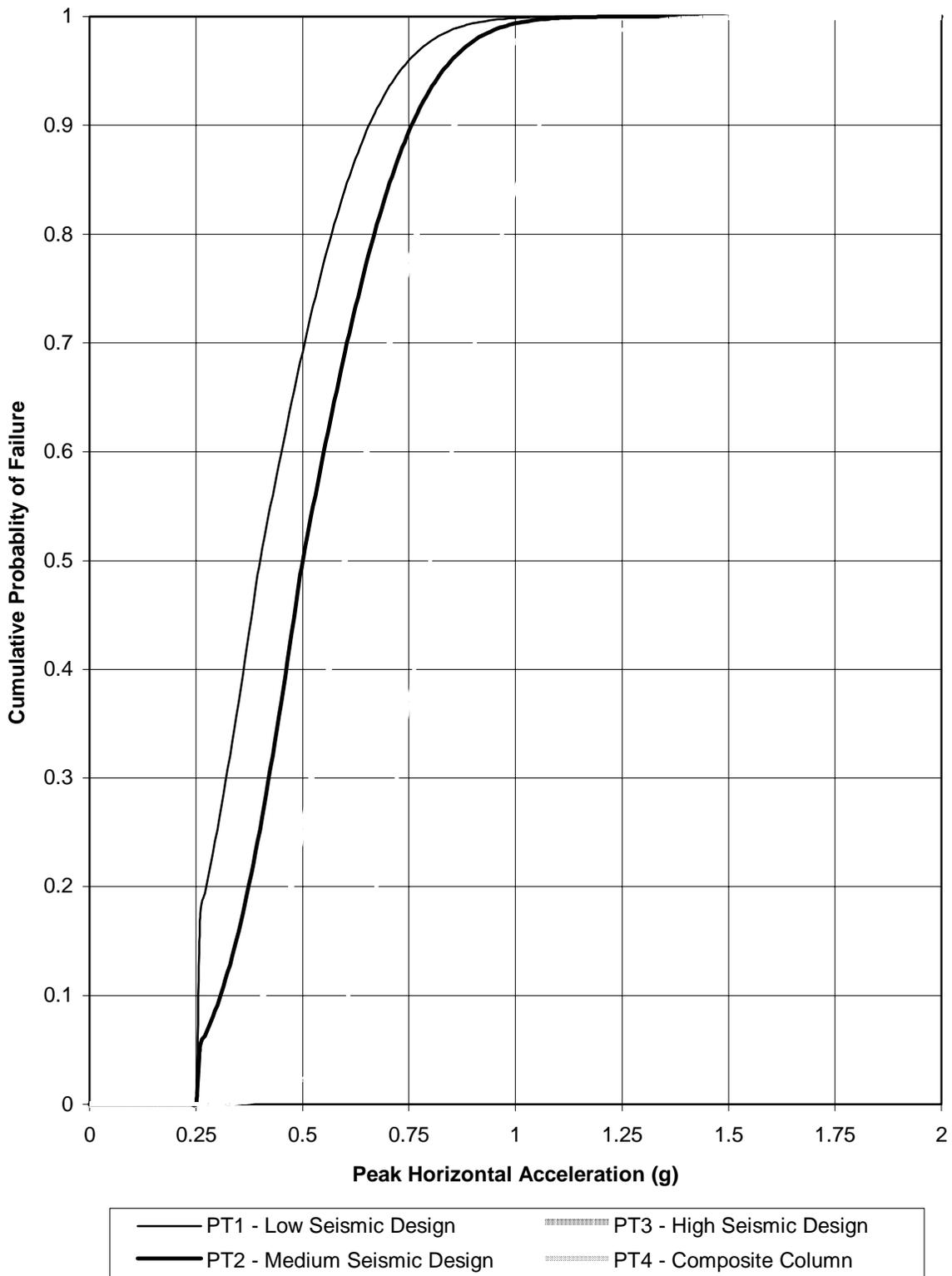


Figure C.25 Utilities Working Group Fragilities for 500 kV Potential Transformers (PT5, PT6, PT7, PT8)

