PRA Panel Proponent #2 Report

January 8, 2013

1 Spurious Operation Probability Assessments

1.1 General comments and discussion

This opening discussion is intended to provide general commentary relating to my assessments that set the context and bounds on the applicability of the SO probability and duration values I am recommending below.

Broadly, the assessments that I am making here consolidate many potential case-specific factors into a single SO probability (or duration) estimate. There are many factors associated with cable installations in plants that have either not been explicitly tested or found to have a minimal effect on SO events. I am following the recommendations of the PIRT panel in this regard. Factors that have been assumed to not substantially impact SO likelihood or duration include many routing configuration variations include:

- Conduits versus tray versus air drop,
- Bundled cables versus random fill arrangements,
- Straight cable runs versus bends or risers,
- Vertical versus horizontal routing,
- Raceway fill,
- The specific position of a cable within a raceway,
- Fire retardant coatings, tray covers, or raceway fire barrier systems,
- Base ampacity loading levels, and
- Cable/conductor size.

In addition, the PRA expert panel chose to eliminate some additional factors given either a lack of data upon which to base a unique treatment or no known applications. The impact of these factors remains unknown and subject to speculation, but no data. Hence, the application of these results to these configurations is uncertain. Configurations to which these results should not be extrapolated, or that should be extrapolated only with significant caution, include:

- Multi-circuit trunk cables,
- Panel wiring (wiring within an electrical cabinet)

The assessments are intended to cover control circuits only including integral indication functions associated with those control circuits. Two applications where these assessments explicitly do not apply are:

- Power cables, and

- Instrumentation circuits/cables.

In the specific case of instrumentation circuits, the PIRT panel provided an extended discussion of circuit design types and potential circuit faulting modes and concerns, but concluded that there is no applicable test data to characterize these circuits and their behavior given cable failure. I concur with this assessment. The results here are not, in my judgment, applicable to instrumentation circuits.

One final consideration is the fire exposure mode to which the cables are subjected (i.e., direct flame exposure, plume type exposures, and lower intensity hot gas layer type exposures). In the case of spurious operation probability, all modes are subsumed into a single probability estimate and this seems consistent with the available data. In the case of SO signal duration, there is evidence that the fire exposure mode does impact duration with longer duration signals being associated with less intense fire exposure conditions and longer times to cable failure. However, I do not see this as a practical consideration for most PRAs. In my experience, risk-significant PRA fire scenarios are generally dominated by flame/plume scenarios. It will be difficult for an analyst to take credit for shorter SO signal durations based on flame exposure because fire size/intensity will determine whether a cable near the fire is in the flame or the plume. Peak fire intensity is, however, treated as an aleatory uncertainty in the analysis methods so that even for a single fire source and a single target cable, sometimes the cable will be in the flame and sometimes it will be in the plume. It seems to me that the analysis will be forced to defer to the somewhat more conservative (i.e., longer) SO signal durations associated with plume exposures for virtually all scenarios. Hence, I have provided, but see little use for, recommendations relative to SO signal duration based on exposure mode.

1.2 Summary tables

Provided below are the three summary tables associated with, respectively, the single break cases, the double break for ungrounded ac, and the double break for ungrounded dc circuits. The details for how the table were developed are provided in Chapters 2 (single break) and 3 (double break).

	Probability of Spurious Operation (Control Cable – Single Break)									
	AC						DC			
	Grounded AC			Ungrounded AC (Individual CPTs)			Ungrounded DC or Distributed Ungrounded AC			
	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	Aggregate	Intra-Cable	Inter-Cable	GFEHS*	Aggregate
	1	2	3	4	5	6	7	8	9	10
1. TS target cable	0.4 (0.25-0.5)	5.0E-3 (5.0E-4 – 0.01)**	0.4 (0.25-0.5)	0.7 (0.4-0.8)	5.0E-4 (5.0E-5 – 1.0E-3)**	0.7 (0.4-0.8)	0.4 (0.25-0.5)	5.0E-3 (5.0E-4 – 0.01)**	0.16 (0.10-0.25)	0.50 (0.33-0.63)
2. TP target cable		2.5E-2 (0.01-0.05)**			2.5E-3 (0.001-0.005)**			2.5E-2 (0.01-0.05)**		
3. Cable includes a grounded metal foil shield wrap	0.08 (0.01-0.15)	☒	0.08 (0.01-0.15)	0.6 (0.3-0.7)	☒	0.6 (0.3-0.7)	0.50 (0.25-0.72)	☒	0.30 (0.20-0.40)	0.65 (0.40–0.83
4. Cable includes an un-insulated grounded drain wire	If needed, use same values as for TS / TP base case (Rows 1 and 2 Columns 1-3 as appropriate to specific case)			If needed, use same values as for TS / TP base case (Rows 1 and 2 Columns 4-6 as appropriate to specific case)			If needed, use same values as for TS / TP base case (Rows 1 and 2 Columns 7-10 as appropriate to specific case)			
5. Armored 7/C Cable	0.01 (0.002-0.02)	☒	0.01 (0.002-0.02)	0.5 (0.2-0.6)	☒	0.5 (0.2-0.6)	0.72 (0.2-0.82	☒	0.5 (0.25-0.65)	0.85 (0.40-0.94)

* GFEHS = Ground Fault Equivalent Hot Short

** for these cases uncertainty bounds are cited as 5th and 95th percentile values rather than quartiles.

Double Break Ungrounded AC Powered from a CPT*						
Cable Configuration	Conductor shorting modes of interest					
	Intra + Intra cable short	Intra + Inter cable short	Inter + Inter cable short	Intra + ground cable short	Inter + ground cable short	Aggregate result
	1	2	3	4	5	6
1. TS insulated source and target cables	0.50	3.5E-4	N/A (incredible)	Delete this column consistent with second note below (◊)	5.0E-4 (5.0E-5 – 1.0E-3)**	0.50
2. TP insulated source and target cables		0.018	6.3E-4		2.5E-3 (0.001-0.005)**	
3. Cable includes a grounded metal foil shield wrap	0.36	N/A	N/A		N/A	0.36
4. Armored 7/C cable	0.25	N/A	N/A		N/A	0.25

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.

◊ Intra cable shorts that mimic the fault mode of ground fault equivalent hot shorts are included under the intra + intra cable short column.

Double Break Ungrounded DC*

Cable Configuration	Conductor shorting modes of interest					
	Intra + Intra cable short	Intra + Inter cable short	Inter + Inter cable short	Intra + ground cable short	Inter + ground cable short	Aggregate result
	1	2	3	4	5	6
1. TS insulated source and target cables	0.16	2E-3	N/A	Delete this column consistent with second note below (◊)	N/A	0.16
2. TP insulated source and target cables		0.018	6.3E-4		4.0E-3	0.17
3. Cable includes a grounded metal foil shield wrap	0.25	N/A	N/A		N/A	0.25
4. Armored 7/C Cable	0.52	N/A	N/A		N/A	0.52

*Shaded black cells are considered implausible but not incredible. Cells marked "N/A" are considered incredible or physically impossible.

◊ Intra cable shorts that mimic the fault mode of ground fault equivalent hot shorts are included under the intra + intra cable short column.

2 Single Break Cases

Table XX contains a summary of the individual single-break case assessments. The following text provides the specific assessment results in a consolidated format. The single break cases are organized here based first on the power source type (i.e., 1.1.1 is grounded ac, 1.1.2 is ungrounded ac, 1.1.3 is ungrounded dc) and secondly based on the cable type variations moving down the table rows.

One point to note is that my analysis of each of the individual single break cases explicitly assumes the circuit of interest is a single actuation device as the target (e.g., an SOV, other solenoid, or single relay type circuit). The result would be different for a circuit where there are multiple targets present such as an MOV with two interacting targets present. The MOV case is dealt with via a fault tree structure described elsewhere.

2.1 Grounded ac Power Source (Case Columns 1-3)

For the grounded ac power source, most assessments are based on direct data analysis. All cases provide some relevant test data with the exception of the drain wire case (row 4) which has been deleted by the panel. The case with the least data is the shield wrap case (row 3). This case is analyzed by extrapolation.

2.1.1 Base Case: TS Target Cable (Cases 01-01 through 01-03)

This specific circuit case (single target / grounded ac) has not been tested explicitly but can be analyzed by extrapolation from the MOV testing that has been done. Looking at the MOV circuits based on the target approach appears valid. I have included some consideration of HS events for the ‘T4’ conductor, the passive target, because T4 was a current-carrying target. I use T4 mainly to validate my understanding of how circuit-to-cable wiring configuration impacts the SO probability. I do not consider hot shorts to spare conductors as these carry no current so the quality of the shorts is unknonw.

In my opinion, the TS intra-cable shorting base case (case 01-01) is a strong anchor for all of the other individual shorting mode cases for this power configuration (grounded ac). That is, the intra-cable base TS case should have a higher likelihood than any of the other individual shorting mode and cable type cases considered for grounded ac-powered control circuits. This will be reflected in my remaining assessments.

I will also use this value as an anchor point when considering un-grounded ac and dc circuits, although more as a reference/comparison point than as a bounding case. However, once the corresponding single-break, intra-cable shorting case has been determined, that case will become the bounding anchor point for their respective power source configurations just as the case here bounds all cases for grounded ac circuits.

The findings of the PIRT panel that the SO probability numbers are only weakly dependent on the insulation type do not appear to have held up well given the more detailed data analysis work. The differences are not huge, but probably large enough to warrant separation of the two cases. As a practical matter, the two aggregates for TS and TP target cables are very close to each other with the TS being the higher of the two. Having one aggregate number applicable to both would allow analysts to do the analysis without the need to determine the cable type and that is clearly a desirable simplification. However, it may be a bit of a stretch given the numbers. An analysis could always begin with the higher TS numbers and refine if the specific cable type can be determined. At this point I no longer recommend combining of the two cases into one number; rather, I recommend that the two cases remain separate with different answers.

2.1.1.1 TS Intra-cable shorting (Case 01-01):

One way to look at the problem is to simply look at one target at a time. The HS/SO statistics for the three individual targets for the typical MOV circuit work out as:

- T4 - 19/53=0.36
- T5 - 26/53=0.49
- T6 - 27/53=0.51

T5 and T6 are clearly aligned and T4 appears to be different. I believe the behavior of T4 further validates the view illustrated in the NEI tests that the conductor-to-circuit wiring configuration is an important effect. For all of the NRC/SNL testing, T4 was consistently placed adjacent to a ground conductor and this likely reduced the overall likelihood of a hot short to this conductor. This is a real effect that should be considered when assessing the typical behavior of a circuit given cable failure.

Given this, for my input I started from the active target T5&T6 base numbers of essentially 0.5. There are, however, two factors leading to a modest conservative bias in the test data (a higher likelihood of SO in testing that in reality):

(1) Most of the circuit tests have used the most conservative of the possible a cable-to-circuit explored in the NEI tests (the so-called source-centered configuration). The wiring configuration appears to

have contributed to an overall variation of roughly 20% from the most conservative to the least conservative wiring configuration. For my analysis, I will reflect this as a +/-10% aleatory uncertainty relative to the median value. Hence, I assume the median value would be roughly 10% less than the base value seen from the testing. Again, the slight difference in HS count for the T4 target appears to bear out this behavior. In reality, the actual circuit-to-cable wiring will likely be unknown so in the average, it is appropriate to provide a value based on random conductor arrangement and allow for the wiring configuration as an uncertainty factor rather than biasing the median value upwards to account for the most conservative wiring configuration.

(2) The second conservatism is that the tests have left spare conductors ungrounded and that is not consistent with common electrical practice. Given a grounded ac circuit, the grounding of spare conductors would tend to reduce likelihood of SO and increase likelihood of fuse blow. Assuming most applications will ground spare conductors; the SO likelihood would be reduced compared to the test results. Specific numbers are not available to characterize this impact, but my judgment is that grounding of spares would have a similar effect as the wiring configuration. That is, the wiring configuration is mainly an issue of the proximity of sources and targets to mitigating conductors (grounds). By adding more grounded/mitigating conductors, one is mimicking changes in wiring configuration. Hence, my median value reduces the base value by an additional 10% based on this effect.

I am also looking forward to the TP case. I think that in the aggregate, the likelihood of SO for TS and TP target cables is essentially the same and that driving towards a single answer for Cases 1_3 and 2_3 is desirable.

Given these factors, my specific probability estimates are as follows:

- The base number from testing (simple ratio) is roughly 0.5 given the conservative nature of the test data and only the active targets. Given the test biases, I have assigned that value to the upper quartile value.
- For the median value, I have adjusted the base number down to 0.4 reflecting a reduction to about to 80% of the base number given two factors each impacting the result by about 10% and assuming the two are independent (1.0*0.9*0.9=0.81).
- The lower quartile is judgment-based. I tend to think more in terms of 5th/95th type values (high confidence limits). In this case I would place a 5th percentile high confidence value at about 0.1 reflecting that I have very high confidence that the SA probability is at least 1-in-10. Since the exercise requests quartiles, I came up with a value of 0.25 as the lower quartile. No formal analysis, simply judgment.

Case 01_01 summary:

Median	0.40
Lower Quartile	0.25
Upper Quartile	0.50

2.1.1.2 TS Inter-Cable Shorting (case 01-02):

In my opinion, this case is grossly over-estimated based on summary count table because of the way in which inter-cable shorts got counted and the test configuration that led to all observed cases for TS insulated cables.

The version of the table I worked from showed 5/53 as the simple count, but this strikes me as a significant distortion of the behavior. The main problem is that all of the observed inter-cable SO events came from the EPRI tests involving one multi-conductor cable bundled with three single conductor cables. This does not actually match the base case which assumes co-located multi-conductor cables. Hence, the 5 cases cited should be substantially discounted compared to the base case here.

Despite many opportunities for interaction, there has not been a single case in testing where a direct TS-TS inter-cable SO has occurred between multi-conductor cables. Hence I see the testing for the actual base case as being more of a 0/50 sort of case.

There is one relevant case to consider. During CAROLFIRE, there was one case on the IRMS where a TS-TS inter-cable short formed as a primary failure mode. The mitigating consideration here is that the IRMS is non-specific as to source/target configuration; that is, it says only that conductors in two separate multi-conductor TS cables shorted together before any other failures were observed. While not an actual SO event, the IRMS does indicate that such interactions can occur. The SO event would be dependent on the random chance that one conductor was a compatible source and the other the target of concern.

Regardless, the lack of any other cases outside of the one IRMS event argues for a very low probability of occurrence. Overall I have estimated this case as of very low likelihood with high uncertainty, especially on the lower side.

- My median estimate is 0.005 based on the insights noted above but not neglecting the insight from the IRMS tests.
- My upper bound estimate 95th percentile for this case would be roughly 0.01. This reflects a relatively high confidence that the likelihood of this case is very low indeed. In this case, I prefer not to estimate the upper quartile value.
- My lower bound high confidence limit (5th percentile) would be 0.0005 reflecting that my uncertainty is greater on the low side (a factor of 10) than on the high side (a factor of 2). This reflect a case where my median value is really a best estimate given current data, and my assessment is that, if that best estimate is wrong, it is unlikely to very much higher, but could be much lower. Again, I would prefer not to estimate the lower quartile value.

Case 01-02 Summary:

In this case I am giving 5th/95th percentile values rather than quartiles. I think this case is better expressed in this manner. Having a high confidence upper bound value will be more useful for a case like this that is considered very low likelihood.

Median	0.005
~~**Lower Quartile**~~ **5th percentile**	0.0005
~~**Upper Quartile**~~ **95th percentile**	0.01

2.1.1.3 TS Aggregate Value (case 01-03):

The aggregate is comprised of intra-cable and inter-cable. For TS inter-cable is so low as to be a non-contributing factor. The inter-cable case/value is only of interest if intra-cable shorting modes are unable to case a SO event. My recommendation is to use the TS intra-cable values (01-01) as effective aggregate. The inter-cable case (01-02) is only of interest in the event that intra-cable shorting cannot cause an SO event.

Case 01_03 (aggregate) summary:

Median	0.40
Lower Quartile	0.25
Upper Quartile	0.50

2.1.2 TP Target Cable (Cases 02-01 through 02-03)

The analysis here parallels that for the TS target cable base case and many of the comments provided in Section 1.1.1.1 apply to the TP cable as well. In particular, the same conservatisms related to wiring configuration and grounding of spares apply and I do apply the same adjustment/reduction factors to the experimental data in determining my final values.

I also want to not that the findings of the PIRT panel where that the SO probability numbers are only weakly dependent on the insulation type do not appear to have held up well given the more detailed data analysis work. My analysis verified that while TP cables may yield very slightly lower SO event probabilities, the differences are quite small and well within our uncertainty bounds.

Overall, my recommendation is to use the same SO probability numbers for the TP intra-cable (02-01) and aggregate (02-03) cases as for the corresponding TS cases (01-01 and 01-03 respectively) . My analysis for these cases is aimed at validating this approach as compared to coming up with independent answers for these cases. As a practical matter, the two aggregates for TS and TP target cables are very close to each other with the TS being the higher of the two. Having one aggregate number applicable to both would allow analysts to do the analysis without the need to determine the cable type and that is clearly a desirable simplification.

In contrast, my judgment is that the likelihood of SO events associated with inter-cable shorting modes is far higher for TP cables (02-02) than for TS cables (01-02). Hence I treat this case explicitly. I still judge the contribution of inter-cable shorting to be small compared to the intra-cable case for TP cables, so I still arrive at a common aggregate value for TS and TP.

2.1.2.1 TP Intra-cable (case 02-01):

Looking at the single target cases again (as in Case 1_1), the raw numbers on this one comes out at roughly:

T4: 10/32=0.31

T5: 15/32=0.47

T6: 12/32=0.38

The raw numbers are slightly lower than the number seen for the TS cable. Again, T4 is a moderate outlier with a slightly lower number. T5 and T6 have a slightly higher variability, but that is probably due in part to the smaller test set and some higher level of aleatory uncertainty for this case. Overall, the raw number from testing for the single target case looking at the average of the T5/T6 giving about 0.43 as compared to the 0.5 value obtained for TS cables.

For this case the same testing biases as noted for Case 1_1 (TS intra-cable) at least nominally apply (for wiring configuration and for un-grounded spares in testing), but there may be a somewhat lower bias for the TP target cable that for the TS cables. Data to quantify this is more limited, but the fact that the T4 hot short probability is comparable to that seen in the TS case (0.31 for TP versus 0.36 for TS) also argues for some effect, although less overall difference between the T5/T6 number and the T4 number. Testing did show that TP cables tended to have more wide-spread conductor involvement in shorting groups; that is, once shorting begins, many conductors tended to become involved as compared to TS cables where the shorting was somewhat more selective.

If I applied the exact same numerical adjustment factors to this case as to the TS case, I would get a median value of 0.35, marginally lower than the TS number at 0.40 (case 01-01). However, if I apply a somewhat reduced correction, the numbers become even closer.

Overall there appears little basis for making a strong distinction between TS and TP cables relative to intra-cable SO likelihood. This is consistent with the findings of the PIRT panel as well. As a result, my recommendation is that the same SO probability values and uncertainty apply to both TS and TP base cases.

Case 02_01 summary (same as case 01_01):

Median	0.40
Lower Quartile	0.25
Upper Quartile	0.50

2.1.2.2 TP Inter-cable case (case 02-02)

This is a difficult case to assess. Inter-cable TP-TP interactions were observed during the EPRI testing (2000) but the configuration is not typical (single conductors surrounding a multi-conductor cable). It is far too easy to dismiss the EPRI tests and then say "we never saw this in any other testing." However, the other tests never looked for this effect. By the time of CAROLFIRE for example, TP-TP inter-cable hot shorting was considered "settled science" and plausible. Hence, none of the follow-up testing programs has been designed to look for TP-TP inter-cable interactions.

The raw results table nominally indicated the following spurious operation results for TP-TP inter-cable:

- 6/32=0.19

This result undoubtedly overstates the probability because all of the identified cases involved the EPRI single conductor cables interacting either with the multi-conductor cable or with another single conductor cable.

The problem with simply dismissing these results is that none of the other test programs has explicitly sought evidence of inter-cable TP-TP interactions. This is because, as stated in CAROLFIRE, "…the NEI/EPRI tests had already demonstrated that TP-to-TP interactions are a plausible mode of cable failure leading to spurious actuations so these types of faults were not examined in CAROLFIRE" (NUREG/CR-6931-V1 pg. 77). The lack of other SO cases from testing must be seen in this light. There were no explicit attempts to set up or monitor for such interactions; hence, not seeing them is not strong evidence for their rarity.

Overall, the available data must be taken as very poor for this case. As stated in CAROLFIRE and as noted above, at the time the NEI tests had established the plausibility of this failure mode. I am recommending that the findings of the prior expert panel stand in this one case. Bottom line is that we know TP-TP can occur with greater likelihood than TS-TS. We have not attempted to investigate this in any of the more recent test programs. We are stuck with, effectively, the same information considered by the original expert panel. The original expert panel placed an estimate of 0.01-0.05 on this case (see case B-8 in Table 7-2 of TR 1006961). Lacking any evidence to the contrary, I concur with this estimate and see no reason to change it. I am taking the prior panel values as the upper and lower quartiles. I place the median at 0.025 which is somewhat below the midpoint as I think the uncertainty is greater on the high side than the low side (we may easily be underestimating this case).

Case 02_02 summary:

Median	0.025
Lower Quartile	0.01
Upper Quartile	0.05

2.1.2.3 TP Aggregate Value (case 02-03):

The aggregate is comprised of intra-cable and inter-cable. As with TS, for the TP cables inter-cable likelihoods are low enough that they can be ignored in comparison to intra-cable shorting. The inter-cable case/value is only of interest if intra-cable shorting modes are unable to case a SO event. My recommendation is to use the TP intra-cable values (02-01) as effective aggregate. The inter-cable case (02-02) is only of interest in the event that intra-cable shorting cannot cause an SO event. This also allows for both the TS and TP base cases to have the same overall aggregate value in general analyses.

Case 02_03 (aggregate) summary (same as 01_03):

Median	0.40
Lower Quartile	0.25
Upper Quartile	0.50

2.1.3 TS with Shield Wrap (Cases 03-01 through 03-03)

This analysis assumes both a robust shield wrap (not simply aluminized mylar) and that the shield wrap is grounded. In addition to the shield wrap, a drain wire may or may not be present and the results would still apply. If the shield wrap is not grounded, the base case 1_1 should apply. If a cable has just a mylar shield wrap then the base case 1_1 should apply.

This is a case for which we have only three tests all based on a Japanese manufactured cable. No SO events were observed in these three tests and this does tend to support the supposition that a robust grounded shield wrap will reduce SO probability, but the evidence is rather weak. Hence, we must extrapolate from other cases including, in particular, Case 1_1 (TS-intra) and Case 5_1 (armored-intra).

2.1.3.1 Shield Wrap Intra-cable case (case 03-01):

The presence of a robust shield wrap introduces a much enhanced ground plane which is a mitigating effect for grounded circuits. The likelihood of interactions between the source conductors and ground goes up, and likely by a significant amount compared to the base case (TS-no shield). The only real question in my opinion is whether or not the shield has an effect as strong as armor. I do not expect the effect to be any stronger than armor, so the problem is bounded between these two cases. My assessment is as follows:

- For the median value, my judgment is that the shield wrap will reduce the likelihood of SO by a factor of 5 compared to the base case 1_1 (TS-intra). This would put the median value at 0.08.
- In this case the uncertainty is high. My judgment is that the "real" number is unlikely to be very much larger than the cited median value so I would place the upper quartile at 0.15 (roughly a factor of 2 on the high side).
- For the lower quartile value, I recommend using the median value for armored cable (Case 5_1) which in my assessment was 0.01. I doubt that the shield wrap is quite as effective at the armor proved to be, but there is a significant chance that the shield wrap would have a stronger effect

than I am assuming so the “real” number could be significantly lower than the median I have cited.

My quartiles are intended to reflect broad uncertainty especially towards lower values. I may be *slightly* underestimating the median value but if I am overestimating it, then I may be overestimating it by a wide margin. At most, the effect may match that of the armor.

Case 03_01 summary:

Median	0.08
Lower Quartile	0.01
Upper Quartile	0.15

2.1.3.2 Shield Wrap Inter-cable case (case 03-02)

Inter-cable hot shorting through a robust grounded shield wrap independent of ground is considered implausible.

2.1.3.3 Shield Wrap Aggregate Value (case 03-03):

See case 03-01 given that the aggregate for this case is entirely intra-cable. Case 03_03 summary:

Median	0.08
Lower Quartile	0.01
Upper Quartile	0.15

2.1.4 TS with Drain Wire (Cases 04-01 through 04-03)

The set of cases involving cable with drain wire (case row 4) was labeled as not applicable (NA) by the panel because use of a cable with drain in an ungrounded circuit is considered unlikely. If the case is encountered in practice, my recommendation is that analysts defer to the corresponding base case estimates for either a TS or TP cable as appropriate (case rows 1 and 2). For an ungrounded ac circuit involving separate CPTs, a drain wire would likely have little or no effect on spurious operation likelihood.

2.1.5 Armored Cable (Cases 05-01 through 05-03)

The following comments apply to some extent to all cases associated with the armored cables.

My analysis is based on examination of the Duke test report. Because the report is proprietary, I cannot report the results in detail here. However, certain considerations were included that can be described here.

First is the fact that the motor starter relays were mechanically and electrically interlocked. Hence, it was not possible for both motor starters to pick up at the same time. The voltage data for these devices was, however, taken upstream of the interlock as shown in their electrical diagrams. Hence, had both targets seen hot shorts, this would be reflected in the data, at least nominally.

The second factor is that the Duke tests used a relatively slow data scan rate (15s) so that the data often missed the voltage and current pickup associated with hot shorts and spurious actuations. The test report does include alternative observations of the SO events based on the actual lock in on the motor starters so it is unlikely that any actual SO events were missed. Indeed, it also appears that SO duration times were determined independently (e.g., based on visual observation) since most were reported durations were less than full data scan cycle. The main shortcoming that the slow data rate presents is that it is not possible to determine if or when both motor starter relay conductors may have taken hot shorts with any reliability. It appears that similar to other tests, many cases saw hot shorts to both conductors as evidenced by increased voltage and current reading on both the C3 and C8 relay targets. However, the slow scan rate makes it impossible to tell what the peak values were. Hence, analysis of the data similar to other tests where the active targets are counted individually is not possible with the Duke data.

The SO event counts reported by Duke reflect those cases where either of the two active targets sees a SO signal. An alternate count based on a specific target (i.e., either relay as an individual target) seeing a SO signal (i.e., to suit the single target present case) is simply not possible. Given the comparatively short duration of the SO signals reported by Duke for the armored cables compared to the non-armored cable tests, it does not appear appropriate to simply apply a reduction factor based on the non-armored tests. Clearly, duration and timing play a key role in the behavior leading to both targets seeing spurious operation signals and the armored and non-armored tests simply do not align well in this regard.

Given the relatively course data, I have taken the raw numbers as if they were single target circuits. This may represent a very modest conservatism, but seems to be the only reasonable way to look at the data without introducing potentially unwarranted optimism.

2.1.5.1 Armored Cable Intra-cable case (case 05-01):

The tests for grounded ac and armored cable are sparse, but some information is available. I have included both the EPRI tests and the tests performed by Duke based on their proprietary test report.

The EPRI test showed 1/7 spurious operations, but that one case is suspect due to a violation of the cable bend radius. The Duke testing included a fairly large number of additional cases with no spurious operations observed.

Overall, the testing shows that the presence of the armor has a powerful effect on spurious actuation likelihoods for grounded ac circuits. Given only one suspect event out of a significant number of trials, the probability of SO for this configuration is clearly very low.

- For the median, I place the SO likelihood at 0.01. That is roughly consistent with the data considering the total number of trials available.

- For the upper quartile, I assume the uncertainty towards the high side is modest. I recommend an upper quartile of 0.02.
- For the lower quartile, I judge that the uncertainty towards the low side appears much higher than that towards the high side. That is, the “real” number may be much lower than the median value cited here, but is not likely much greater. I would recommend a value of 0.002 for the lower quartile.

Case 05_01 summary:

Median	0.01
Lower Quartile	0.002
Upper Quartile	0.02

2.1.5.2 Armored Cable Inter-cable case (case 05-02)

Inter-cable hot shorting through grounded armor independent of ground is considered implausible.

2.1.5.3 Armored Cable Aggregate Value (case 05-03):

See case 05-01 given that the aggregate for this case is entirely intra-cable.

2.2 Ungrounded ac Power Source (Case Columns 4-6)

This set of cases all assume ungrounded ac power sources based on individual ungrounded CPT circuits with each circuit contained in its own multi-conductor cable. Hence, inter-cable spurious operations would only occur given that the CPT for one circuit (one aggressor cable) energizes a second circuit (second target cable). However, separate ungrounded CPTs are not compatible power sources. Hence, single hot shorts between separate CPT circuit cables are not capable of producing a spurious operation. For one circuit to power another, both sides of a common CPT must act as sources against the specific target conductors in the target circuit. This requirement sharply reduces the likelihood of direct inter-cable hot shorts leading to spurious operation in comparison to the grounded ac case where only a single inter-cable hot short is needed.

I include in this assessment the recognition that one of the two hot shorts may be the result of a hot-short equivalent ground fault situation. That is, if one side of the aggressor circuit power supply and one side of the target circuit end device become grounded, then a single additional inter-cable hot short could cause spurious operation provided the aggressor circuit fuses remain intact. Overall, the inter-cable shorting configurations leading to spurious operation are quite specific and must occur concurrently. As a result, in my judgment, this failure mode would be considered improbable and is assigned a very low likelihood consistent with other cases judged improbable.

I also note that we have no data at all to directly support most of these cases. There is limited data from the CAROLFIRE program for an ungrounded CPT-driven MOV circuit with TS and TP cables, but at most for a single circuit per test (no possibility of circuit-to-circuit interactions). Hence, all of the cases are developed based largely on extrapolations between other cases. In particular, I compare across the columns (e.g., grounded ac vs. ungrounded dc for a given cable type) and I may compare across rows (e.g., the TS base case versus armored cable for a given power source configuration).

2.2.1 Base Case: TS Target Cable (Cases 01-04 through 01-06)

2.2.1.1 Intra-cable (case 01-04)

This is a marginally tested case (CAROLFIRE) showing 6/8 spurious operations due to intra-cable shorting. That is very weak evidence but does appear comparable to the corresponding grounded ac case (case 01-01). That is, the grounded ac testing saw a raw 0.6 probability and this case is slightly higher at 0.75 which matches my expectations. The ungrounded ac case should be slightly higher than the corresponding grounded ac based mainly on the fact that for ungrounded circuits, grounded conductors and external grounds do not act as mitigating factors until multiple shorts occur. That is, a single short to ground does not clear circuit protection here (whereas it does for grounded ac) leaving more opportunity for hot shorts and spurious operation given intra-cable shorting.

As to adjustments, the wiring configuration effect of the testing is still a factor. We don't have direct data for this effect for ungrounded ac so I am assuming a similar level of conservative bias (+/-10%) in the data. It is also interesting to note that in all test cases if one active target was hit, the other was also hit. Hence, the numbers for the two conductor targets are identical.

The effect of spare grounding practices is not a factor and no adjustment will be made.

- My median value is based on the raw value (0.75) reduced by 10% (0.75x0.9=0.675) which I round to 0.7.
- My lower quartile value reflects relatively tight uncertainty bounds on this case. It appears reasonable that a value of 0.4 (the median value for case 01-01) would be appropriate as the lower quartile and not lower.
- My upper quartile value again uses 0.8 as a likely upper bound for any and all cases.

Case 01_04 summary:

Median	0.7
Lower Quartile	0.4
Upper Quartile	0.8

2.2.1.2 *Inter-cable (case 01-05)*

There is no data whatsoever for this case. Hence, one must compare to other cases. Here I would compare to case 01-02, the base case TS inter-cable for grounded ac. Given that the ungrounded separate CPT case must involve a more complicated shorting arrangements for both the source and target cables, this mode must be far less likely (i.e., than case 01-02). The question is how much lower the probability would be.

The PIRT panel did not explicitly consider this power source configuration in it's deliberations, rather, it was added later in the process as the final tables were re-organized for use by this expert panel. In my view, the ground equivalent hot short configuration is really the only shorting configuration that has any real chance for causing this mode of spurious operation failure. Concurrent direct conductor to conductor shorts between specific conductor pair on two separate multiconductor cables seems implausible.

Overall, given the highly specific nature of the required faults, I would assess this case as a factor of 10 less likely to occur than would be a single direct conductor-to-conductor hot short induced spurious operation (i.e., 1/10 the values given for case 01-02).

Case 05_02 summary:

Median	5E-4
~~Lower Quartile~~ 5th percentile	5E-5
~~Upper Quartile~~ 95th percentile	1E-3

2.2.1.3 *Aggregate (case 01-06)*

See values for case 01-04 given that the contribution of inter-cable shorting is trivial compared to the intra-cable value.

2.2.2 TP Target Cable (Cases 02-04 through 02-06)

2.2.2.1 Intra-cable (case 02-04)

This is another case with a minimal data set (5 tests) from CAROLFIRE. The raw number here is roughly 60%-80% (3/5 for T5 and 4/5 for T6) given a small number of available trials. As was seen for the TS base case, the lack of power source grounding does appear to increase likelihood, although wiring configuration is an issue.

Overall, the TP intra-cable numbers are again consistent with those seen for TS cables (which had a raw SO probability of 0.75). Given the overall sparse data, I do not recommend a separate analysis of the TP data; rather, I recommend that the same value be used for both cases (i.e., the numbers for case 02-04 should match those for case 01-04).

Case 02_04 summary:

Median	0.7
Lower Quartile	0.4
Upper Quartile	0.8

2.2.2.2 Inter-cable (case 02-05)

My analysis of this case parallels that described for case 01-05 (TS). Overall, given the highly specific nature of the required faults, I would assess this case (02-05) as a factor of 10 less likely to occur than would be a single direct conductor-to-conductor hot short induced spurious operation (i.e., 1/10 the values given for case 02-02).

Case 02_05 summary:

Median	2.5E-3
~~Lower Quartile~~ 5th percentile	1.0E-3
~~Upper Quartile~~ 95th percentile	5.0E-3

2.2.2.3 Aggregate (case 02-06)

See values for case 02-04 given that the contribution of inter-cable shorting is trivial compared to the intra-cable value. Note that both the intra-cable and aggregate number for the TS and TP cables are again the same. This is intentional and a recommended approach to simplify analysis given only minor statistical differences between these cases.

2.2.3 TS with Shield Wrap (Cases 03-04 through 03-06)

2.2.3.1 Intra-cable (case 03-04)

We have no data at all for this case. My assessment is based on a comparison between cases 01_04 (TS base case intra-cable) and case 05_04 (armored intra-cable). The effect shown by the armor was a marginal decrease in SO probability (0.5 for armored vs 0.7 for non-armored TS). The armor likely has a much stronger effect than a metal shield wrap as argued in Case 03_01. Hence, my recommendation is to assume an intermediate value for the shield wrap case for ungrounded ac.

Summary for case 03-04:

Median	0.6
Lower Quartile	0.3
Upper Quartile	0.7

2.2.3.2 Inter-cable (case 03-05)

This case is not applicable.

2.2.3.3 Aggregate (case 03-06)

See case 03-04 given that there is not contribution from inter-cable shorting.

2.2.4 TS with Drain Wire (Cases 04-04 through 04-06)

The set of cases involving cable with drain wire (case row 4) was labeled as not applicable (NA) by the panel because use of a cable with drain in an ungrounded circuit is considered unlikely. If the case is encountered in practice, my recommendation is that analysts defer to the corresponding base case estimates for either a TS or TP cable as appropriate (case rows 1 and 2). For an ungrounded ac circuit involving separate CPTs, a drain wire would likely have little or no effect on spurious operation likelihood.

2.2.5 Armored Cable (Cases 05-04 through 05-06)

See Section 1.1.1.5 for general discussion regarding review of armored cable data.

2.2.5.1 Intra-cable (case 05-04)

The data for ungrounded ac with armored cable is exclusively based on the Duke testing. Those tests included eight circuits per test and a fair number of tests. Overall they saw spurious operations in approximately 58% of their circuits.

Similar to other programs Duke used the source-centered wiring configuration known to produce more conservative results. A 10% adjustment for this conservatism appears appropriate. However, their circuit diagram indicates that they grounded one of two spares (conductor 5 is grounded with the armor, conductor 7 is left floating. Given the prevalent role of the armor as a ground, there appears no reason to apply any further reduction based on the presence of one ungrounded spare.

- for the median I recommend a value of 0.50. This is based on the raw result of 0.58 reduced by 10% for the wiring configuration (0.58*0.9=0.52) and rounded to one significant figure.
- for the upper and lower quartiles, I recommend 0.6 and 0.2 based on applying a similar general uncertainty range as I have cited for other cased including the ungrounded ac base case (01_04).

Case 05_04 Summary:

Median	0.5
Lower Quartile	0.6
Upper Quartile	0.2

2.2.5.2 Inter-cable (case 05-05)

This case is not applicable.

2.2.5.3 Aggregate (case 05-06)

See case 05-04 given that there is not contribution from inter-cable shorting.

2.3 Ungrounded dc Power Source (Case Columns 7-10)

There is considerable data for the ungrounded dc power source from DESIREEFIRE, KATEFIRE and the Duke testing. Hence, most of these cases are based on data rather than extrapolation. The major exception is the shield wrap case (row 3) for which there is no test data and extrapolation is required.

Also note that in other cases I have combined the TS and TP (rows 1 and 2) for both intra-cable and aggregate. In the case of ungrounded dc, I am again combining for the intra-cable, but providing different aggregate results. This is because the GFEHS case appears different for the two and is a more significant factor in the aggregate than inter-cable shorting has been for other power source configurations. This mode is likely enough that the aggregate must include it.

Comments on My General Approach to GFEHS Analysis

One of the more significant challenges relative to the dc circuits is, in my opinion, the GFEHS issue. As described in the data analysis results, there were a substantive number of these events observed during the DESIREEFIRE program. The data analysis as presented in the data spreadsheets cites the number of GFEHS induced spurious operation events that occurred for various cable groups and, as a companion datum, the number of "tests" associated with these events. However, note that the companion datum is actually the number of individual circuit trials for each group (i.e., each individual test had more than one circuit present so there are far more circuit trials than there are separate tests). In my view this is the appropriate basis for consideration (i.e., events per circuit trial).

In total, there were 30 GFEHS spurious operation events (16 from intermediate scale and 14 from penlight) in a total of 169 individual circuit trials where the opportunity existed. This is a relatively larger number of events indicating roughly a 1-in-5 to 1-in-6 overall rate of GFEHS spurious operation events (0.18).

One question is the applicability of the Penlight data. In some cases, there are a higher percentage of events associated with Penlight and in others, there are more associated with the intermediate scale tests. Overall (blending all cases), the fractions are quite similar. This is illustrated in the table below:

Test scale	Total circuit trials	GFEHS events	Nominal ratio (events/circuit trial)
Intermediate scale	97	16	0.16
Penlight	72	14	0.19
Both combined	169	30	0.18

The final ratio values are quite similar and well within our general uncertainty. Hence, I see no reason not to simply blend the data. This is also supported by the actual behaviors involved. Based on the testing it is essentially inevitable that the battery bank will be grounded as the result of cable failures. Hence, the only real question is whether or not an appropriate target conductor experiences a short to ground concurrent with the appropriate side of the battery bank (e.g., the positive side) also being grounded.

Another aspect of my GFEHS spurious operation event analysis is that in other cases (e.g., intra-cable shorting modes) I have applied adjustment factors to account for experimental biases related to wiring configuration and the fact that spare conductors were not generally grounded. In the case of GFEHS spurious operation events I don't believe either factor applies. In an ungrounded circuit one would not expect spare conductors to be grounded. With respect to wiring configuration, it is unclear how this would impact the likelihood of GFEHS spurious operation events. There likely is some effect, but we simply have no basis for assessing that effect. Hence, by and large, I will rely on the raw statistics with some consideration of any apparent inconsistencies between the various cases.

Finally, I am making no specific or unique analysis of the MOV circuits, which have two targets available. I don't think in this case that is a significant factor. I am simply counting events per circuit trial. In the case of the breaker trip and close circuits, I would have counted hot shorts to the target conductor (trip or close coil) even if this did not re-position the breaker. That is, if the close coil received a hot short while the breaker was already closed, I consider that a valid GFEHS spurious operation event. It does not appear that this was observed in any of the tests. Consistent with the base data analysis, I am <u>not</u> counting hot shorts to other targets (i.e., spares or indicator lamps) even though such events were observed and are noted in the data tables. The probability of the hot short hitting the correct target conductor is a part of the spurious operation likelihood consideration. It appears that the spurious operation table has counted consistent with this view.

Comments on my analysis of ungrounded circuit aggregate values:

This is the one set of cases where consideration of an appropriate aggregate value is a bit more complicated. In other cases, intra-cable shorting has been so dominant that the value for that particular failure mode was effectively the aggregate, and the inter-cable value was only of interest in cases where intra-cable spurious operations could be analytically eliminated. Here, there are two relatively high probability failure modes that must be considered with appropriate treatment of overlap; namely, intra cable and GFEHS spurious operation events. Generally I am using an 'exclusive or' summation for the two dominant failure modes; namely, intra-cable and GFEHS.

2.3.1 Base Case: TS Target Cable (Cases 01-07 through 01-10)

2.3.1.1 Intra-cable (cases 01-07 and 02-07)

Note that for this case as for others, I plan to combine the TS and TP cables for intra-cable shorting. The data for this and other cases support this simplification. However, unlike other cases, I am not combining for purposes of an aggregate number. The GFEHS case is a significant contributor to the aggregate and is different for the two cable types.

This is a case with a lot of data. Looking at the data, we have a mix of two-target MOV and single target SOV / breaker circuits. In my opinion, there is sufficient data for SOV type circuits (SOV1, SOV2, Large Coil and 1" valve) to form a sufficient set for evaluation. That is, for these cases I am not considering dat from the breaker trip and close circuits and the two MOV circuits. I am also including the Penlight data as I see no reason to exclude this data for intra-cable cases in particular.

For the single target SOV type circuits, and for the case of TS cables, the data appear to show 17/40 spurious operation events for a raw count of 0.43. For the TP cables, the numbers are quite similar showing 15/30 spurious operation events for a raw number of 0.50. Combining the two data sets, yields 32/70 or a raw fraction of 0.46. This will be my starting point. The wiring configuration bias still applies to this case, although spares would not expect to be grounded given ungrounded dc power source so that bias does not apply. Beginning with the raw value of 0.46 and reducing by 10% for the wiring configuration bias yields: 0.46*0.9=0.41. Rounding this to one digit for convenience, my recommended median value is 0.40.

Curiously, this is the exact same value I obtained for the grounded ac intra-cable TP/TS base case. It was not my intent to match these two cases, but the fact that they do match reinforces the conclusions of the PIRT panel and is interesting.

- As described above, my estimate of the median value for this case is 0.40.
- Given the similarities between the ac and dc results, I would recommend the same general uncertainty bands here. Hence, my upper quartile is set at 0.5 and the lower quartile at 0.25.

Case 01_07 and Case 02_07 summary:

Median	0.40
Lower Quartile	0.25
Upper Quartile	0.50

2.3.1.2 Inter-cable (case 01-08)

This case has no new data or insights to offer beyond that considered in Case 01-02. My recommendation is to use the same values here.

Case 01-08 Summary:

Median	5.0E-3
~~Lower Quartile~~ 5th percentile	5.0E-4
~~Upper Quartile~~ 95th percentile	0.01

2.3.1.3 Ground-Equivalent Hot Short (case 01-09)

See Section 2.3 for a discussion of my analysis approach for all GFEHS spurious operation event cases. For the TS cables, there were a total of 14 GFEHS spurious operation events in a total of 87 circuit test trials. This would indicate a nominal probability of this mode of failure of 0.16.

Overall, I think our uncertainty on this mode is perhaps less significant than for many other cases. It appears that this is indeed a relatively likely event and the numbers from the testing are likely pretty accurate.

Case 01_09 summary:

Median	0.16
Lower Quartile	0.10
Upper Quartile	0.25

2.3.1.4 Aggregate (case 01-10)

An exclusive 'or' sum of the two dominant case yields:

Case 01_09 summary:

Median	0.40 + 0.16 - (0.40*0.16) = 0.50
Lower Quartile	0.25 + 0.10 - (0.25*0.10) = 0.33
Upper Quartile	0.50 + 0.25 - (0.50*0.25) = 0.63

2.3.2 TP Target Cable (Cases 02-07 through 02-10)

2.3.2.1 Intra-cable (case 02-07)

See Section 2.3.1.1 for a description of my analysis for the combined TS/TP base case for intra-cable shorting (combined analysis for cases 01-07 and 02-07).

2.3.2.2 Inter-cable (case 02-08)

This case has no new data or insights to offer beyond that considered in Case 02-02. My recommendation is to use the same values here.

Case 02-08 Summary:

Median	0.025
~~Lower Quartile~~ 5th percentile	0.01
~~Upper Quartile~~ 95th percentile	0.05

2.3.2.3 Ground-Equivalent Hot Short (case 02-09)

This is an interesting case and one that in some ways is a bit of an outlier. This is the one case where the disparity between penlight and intermediate scale results is relatively large. In penlight there were six GFEHS spurious operation events in 28 trials for a ratio of 0.21 events per trial. In intermediate scale there were just three GFEHS spurious operation events in 35 trials for a ratio of 0.09 events per trial. I have no particular insight into why the two test scales appear different whereas other cases are far more consistent.

For consistency, I believe it is appropriate to look at the aggregate of the two test scales yielding 9 GFEHS spurious operation events in 63 total trials for a ratio of 0.14 events per trial. This is once again surprisingly consistent with the TS ratios of 0.16 events per trial (see case 01-09). Hence, as in other cases I recommend combining the TS and TP cases into a single case using the numbers seen for the TS cable. I fall back on the TS statistics rather than simply blending the two because of the unexplained difference between the test scale results. I suspect there may be something about the intermediate scale tests that may have made the GFEHS spurious operation events less likely (i.e., there were generally very few TP cables in any given tests whereas in reality there would be many).

Case 02_09 summary:

Median	0.16
Lower Quartile	0.10
Upper Quartile	0.25

2.3.2.4 Aggregate (case 02-10)

See case 01-09 for 'exclusive or' combination.

2.3.3 TS with Shield Wrap (Cases 03-07 through 03-10)

2.3.3.1 Intra-cable (case 03-07)

This is a case with a raw count of spurious operations of 3 events in 7 trials for a nominal raw number of 0.43. This is again a very limited data set. As with other shield wrap cases, I expect the probability numbers to fall somewhere between the TS/TP base case (rows 1/2) and the armored cable case (row 5). The basis for this assessment matches the discussions provided for cases 03-01 and 03-04. Therefore, the raw number seems to be somewhat under the value I would predict based on comparison to the other cases. For example, just one additional spurious operation (4 out of 7) would raise the raw value to 0.57. Overall, I am adjusting my recommended median value up to 0.5 based on an expectation that, based on the armored tests in particular, the ungrounded circuits should see some increase in SO probability given the shield wrap. My upper and lower quartiles are similarly based on a comparison to the TP/TS and armored cable cases.

Case 03_07 summary:

Median	0.50
Lower Quartile	0.25
Upper Quartile	0.72

2.3.3.2 Inter-cable (case 03-08)

This case in not applicable.

2.3.3.3 Ground-Equivalent Hot Short (case 03-09)

This is a case with just 7 trials available. The raw results saw 2 GFEHS spurious operation events in these 7 trials for a nominal ratio of 0.29 events per trial. This is consistent with other effects seen for the shield wrap case. That is, in other cases the behavior of the shield wrap cable has fallen somewhere between the base TS cable and the armored cable. This is true here as well with the TS at 0.16 and the armored cable at 0.50. Overall, I would round the median for this case to 0.3 and assign a similar uncertainty range to other cases.

Case 03_09 summary:

Median	0.30
Lower Quartile	0.20
Upper Quartile	0.40

2.3.3.4 Aggregate (case 03-10)

My recommendation for the aggregate case is based on a simple logical 'OR' combination of Cases 03-07 and 03-09 (given that 03-08 has a trivial contribution to the aggregate.

Case 03_10 summary:

Median	0.65 = 0.5 + 0.3 – (0.5*0.3)
Lower Quartile	0.40 = 0.25 + 0.2 – (0.25*0.2)
Upper Quartile	0.83 = 0.72 + 0.40 – (0.72*0.4)

2.3.4 TS with Drain Wire (Cases 04-07 through 04-10)

These cases were identified by the panel as not applicable (NA) because a cable with a grounded drain wire is not expected given an ungrounded power source.

However, if a case such as this is encountered in actual practice, I would recommend that analysts defer to the corresponding base case (case rows 1 or 2) for intra-cable shorting fault mode and to the shield wrap case (case row 3) for the GFEHS fault mode. The presence of a grounded drain wire could increase the likelihood of the GFEHS so use of the shield wrap case for that mode would be conservative.

2.3.5 Armored Cable (Cases 05-07 through 05-10)

2.3.5.1 Intra-cable (case 05-07)

This case is somewhat difficult given a rather small set of experimental trials. There are also some fairly serious issues with the Duke Energy testing that forms part of the basis for this case. The Duke Energy tests saw ignition of their measurement shunts, and some of the test relay target coils. One of the two relevant tests was ended early due to safety concerns so that only 5 of the 8 circuits present actually failed in testing. I do not consider circuits that did not fail in testing to contribute to the spurious actuation conditional probability statistics so the un-failed circuits are not considered.

My assessment is based in part on the MOV and SOV cases from DESIREE Fire which involved a total of six circuit trials with armored cables. Since three of those trials involved the dual-target MOV circuits, they have been analyzed using the target approach as in other cases yielding an effecting nine total circuit/target trials (MOV tests D-IT-9-MOV2, D-P-22-MOV1, D-P-22-MOV2, and SOV tests D-IT-9-SOV2, D-P-20-SOV1, D-P-20-SOV2). The overall results for these cases are quite consistent. Considering all of the individual targets, there were a total of 6 spurious operation events noted in 9 circuit/target trials for a nominal 0.66 probability of spurious operation.

The Duke Energy tests included 2 tests with ungrounded dc MOV circuits (Tests 13 and 14). It would appear that in Test 13, there were 8 spurious coil operations out of a possible 16, but in some cases the shunts in the circuit burned early in the testing and this may have prevented additional spurious operation events from being observed. More telling is test 14 which was ended prematurely due to safety concerns. The test was ended after just 5 of the 8 circuits had experienced failure. However, all 10 of the target coils in the five damaged circuits experienced spurious operation for a nominal 100% spurious operation ratio. If the two tests are taken exactly as cited, a statistic of on the order of 18 out of 26 spurious operations, or 0.7, is obtained. However, this figure may be a bit low given the problems with burning of the shunts and, in some cases, the coils themselves plus early termination of the second test.

Overall, my assessment is that the test data may slightly under-represent the possibility of spurious operation given a rather small number of trials and substantial testing issues with the Duke Energy test set. I place the nominal value (median) at 0.72 with upper and lower quartiles of 0.82 and 0.2 respectively. In particular, the Duke tests indicate a possibility of a rather high conditional probability given test 14 in particular with its 10 out of 10 spurious operation result. On the other hand, the problems with the Duke Energy testing offer some significant uncertainty and the DESIREE-Fire results also tend to indicate a somewhat lower probability. That coupled with the possible conservatisms in wiring configuration argue that the "real" value could be sharply lower than the nominal experimental value. Hence my lower quartile is substantially lower than the median.

Case 05_07 summary:

Median 0.72

Lower Quartile 0.20

Upper Quartile 0.82

2.3.5.2 Inter-cable (case 05-08)

This case is not applicable.

2.3.5.3 Ground-Equivalent Hot Short (case 05-09)

This is a case with very few trials, but a relatively high number of GFEHS spurious operation events. The date show 6 GFEHS spurious operation events in a total of just 12 circuit trials indicating a nominal ratio of 0.5 events per trial. This is higher than any other case, but is likely due to the prevalent role of the grounded armor in the shorting behavior. That is, with a grounded armor present, the cable conductors would have ready access to that ground plane, and/when if the battery becomes grounded, a GFEHS spurious operation event seems likely. This is also consistent with the fact that for grounded circuits, the grounded armor virtually eliminated spurious operations. Hence, I see no reason to doubt these statistics. I am assigning slightly higher uncertainty bounds for this case given the small number of trials.

Case 05_09 summary:

Median	0.50
Lower Quartile	0.25
Upper Quartile	0.65

2.3.5.4 Aggregate (case 05-10)

The aggregate value recommended is based on a statistical ‘OR’ combination of cases 05-07 and 05-09.

Case 05_09 summary:

Median	0.85
Lower Quartile	0.40
Upper Quartile	0.94

3 Double Break Cases

3.1 Approach to Analysis:

In early panel discussions, I indicated my inclination was to treat the two hot short events required to induce a spurious operation given a double break design by simply assuming two independent events of the specified type (e.g., intra-cable, inter-cable, GFEHS or combinations). Other panelist suggested this would ignore dependency issues citing prior statements by myself and others that “given hot shorts forming within a faulting cable, more than one conductor was typically involved in the shorting behavior.” Other panelists cited this as evidence that, given a hot short to one conductor, hot shorts to additional conductors are not independent events and should be assigned a higher probability of occurrence for multiple hot shorts. Assuming independence would therefore underestimate the probability of spurious operation for the double break designs. I have come to the conclusion that this is an inappropriate interpretation of the prior statements made regarding the involvement of multiple conductors in most of the cable hot shorting cases observed in testing.

While the prior statements remain true, I believe the above description is not a proper interpretation of the effect as applied to this case. To explain further, none of the tests to date have investigated double break designs. As a result, in every circuit failure mode test performed to date there has been just one energizing hot short source potential present. In the ac tests this was the ‘high’ or ‘hot’ side of the ac power source (generally a CPT) and in the dc tests this was the positive battery potential. Shorts between to the opposite side of the power source (i.e., the ‘return’, ‘neutral’ or ground for ac, and the battery negative for dc) and the ‘target’ conductors would not cause a spurious operation. Such shorts were, in fact, a mitigating effect that would prevent or disrupt a spurious operation by causing a fuse blow failure given a hot short to the target conductor. In these tests it was common to see that once the hot short source conductors began shorting to other conductors in the cable, the shorting was rarely limited to just one conductor pair.

With the double break design, there are two energizing potentials that must come into proper shorting configurations in order to cause a spurious operation (both the hot and return sides for ac, and both positive and negative for dc). Two independent hot shorts must form concurrently before a spurious operation can occur; namely, a short between one side of the power source and the conductor for one side of the target end device, and a second separate short between the opposite side of the power source and the opposite side of the target end device. This is a far different condition from that implied by our earlier statement which observed that given that one side of the power source has shorted to one side of the target end device, that same hot short source is also very likely to impact other cable conductors as well.

This would imply that the same side of the power source may well hot short to the conductor associated with the other side of the target end device, but this condition would not induce a spurious operation given double break. However, if one side of energizing power source shorts to several conductors (rather than just one) then spurious operation may actually be less likely because the spurious operation requires that the opposing side of the target end device remain available to receive an energizing hot short from the opposite side of the power source without causing a fuse blow.

Overall, the dependence implied by the earlier statement actually may imply an inverse dependency with respect to the double break spurious operation. That is, if the first of the two required hot shorts has formed there is a certain dependent likelihood that the opposite side of the target end device will also short to the same energizing source (i.e., to the same side of the power source). If a subsequent hot short from the opposite side of the power source were to subsequently form, a fuse blow failure would occur, not a spurious operation.

Other factors that would play some role in this problem are the duration and timing of the short circuits. That is, the two shorts required to cause a SO event on a double break circuit must overlap in time. This is an extremely difficult problem not well represented by the data sets available. For intra-cable based cases, shorts among all conductors tend to overlap in time anyway, so duration and timing likely have little effect on cases strictly related to faults within a single cable (e.g., Column 1). In those cases involving external interactions, either grounds or inter-cable shorts, in reality there would likely be many more potential donor cables surrounding the target cable than were ever present during the tests. Hence, timing constraints would likely be less restrictive than the data sets would nominally indicate. For the purposes of this assessment, I am neglecting these two factors, duration and timing.

Overall, it is my opinion that the value obtained by simply assuming independent hot shorts of the specified type will yield a *moderately conservative* estimate of the spurious actuation probability given that this approach ignores the likely *negative* dependency factors described above. However, without testing we have no basis for quantifying that negative dependency and I am unwilling to speculate on further reducing these values.

Given this assessment, the exercise for most cases becomes somewhat trivial. So long as the prior tables include each of the two individual shorting modes assumed for a case, one simply need multiply the two hot short probability values (e.g., intra-cable plus inta-cable; intra-cable plus GFEHS; etc.). I have calculated the median values but the upper and lower quartile values are easily obtained. For aggregates, I am again doing an “exclusive OR” combination of the dominant modes ignoring trivial contributors to the aggregate.

There are specific set of cases not covered by the base tables. The analysis of these cases is provided in the following two sections. They are specifically those associated with (1) grounded ac circuits where one side of the fault is assumed to arise from a fault to ground and (2) ungrounded ac where a GFEHS situation is involved. These ground fault cases were not separately assessed in the single break cables. For both summary tables, this corresponds to columns 4 and 5. These cases are covered in sections 3.2 and 3.3 respectively.

3.2 Ungrounded ac – double break cases

3.2.1 Columns 1-3

For column 1-3 of the double break summary table, I am applying the results directly from the single break table to the corresponding cases assuming independence of the faults as described in Section 3.1 above. For example, column one is simply the square of the corresponding column 1 values from the single break table. The results (medians only) are shown in the summary table.

3.2.2 Column 4 - intra-cable plus ground fault interactions

For the ungrounded ac – separate CPT power sources cases there was no specific consideration of the likelihood of the GFEHS case. Frankly, I don't see any practical use for Column 4 in practice. The only distinction between the cases in Column 1 and Column 4 is that the one of the two shorts required for the spurious operation occurs via two conductors in the cable shorting to ground for Column 4 versus the same two conductors shorting directly to each other for Column 1. In a practical application, no analyst will make such subtle distinctions when the circuit/cable wiring requirements and the net effect on the circuit are both identical. That is, all of the interactions are occurring based on the faulting of a single cable, and whether and external ground becomes involved is really not relevant to a practical analysis. The fact is, the cable has the required conductors present and a single composite number is desired to reflect the likelihood that shorting among those conductors leads to spurious operation and the involvement of the ground plane is irrelevant.

Overall, as I have argued above, I believe the results I have provided for Column 1 (intra- plus intra-) are conservative and bound the contribution from the very specific faulting configuration assumed in Column 4. I recommend Column 4 be deleted as having no practical application as a unique failure mode and that a note be added to column one citing that the ground fault scenario is subsumed under Column 1. That is Column 1 is redefined as "intra- plus intra- including GFEHS cases involving only the conductors of the target cable and any available ground plane. My values have been assigned accordingly and the value given for Column 1 includes shorting of the type specified for Column 4.

3.2.3 Column 5 - inter-cable plus ground fault interactions

In my analysis of the single break cases, and specifically SB cases 01-05 and 02-05, I already specified that the configuration required for a separate ungrounded ac CPT to power a target circuit involved two concurrent hot shorts, one on each side of the source power supply, and that the most likely mode of such interaction would involve one inter-cable short and a GFEHS. This is identical to the requirement for the double break case. Hence my assessment of the likelihood for double break cases 01-05 and 01-05 are also identical as are the recommended results. The probability estimated provided in the double break summary table are taken direction from the corresponding cases in the single break table.

Column 6 – aggregate values

In this case, I recommend using the values from Column 1 as the aggregates for all rows. The likelihood of the cases involving any level of inter-cable interactions are sufficiently small as to be of interest only when the intra- plus intra- shorting case (Column 1) is not possible given the wiring configuration. If the intra- plus intra- case is possible, then the likelihood of that one case is sharply dominant and acceptable as an aggregate with any small independent contribution from other cases being well within uncertainty bounds. This also simplifies practical application and is consistent with my approach to most other cases.

3.3 Ungrounded dc Double Break Cases

The ungrounded dc double break cases are somewhat easier because we have already looked at the GFEHS problem independently under the single break analysis. Hence, essentially all of these cases are covered by the product of two single break cases.

My comments relative to column 4 of the summary table parallel those provided in Section 3.2.2 above. In my estimates, that case has been subsumed under the probabilities for column 1 as I have no way of discerning the specific case cited in Column 4 nor do I see any practical application for that shorting configuration as an independent case.

My aggregate numbers follow the same approach as for the ungrounded ac cases.

4 Duration

In general, I am not providing detailed recommendations for statistical treatment of spurious actuation signal duration. Based on panel discussions, I generally concur with the approaches being taken by other panelists which are based on fitting of statistical distributions to the test data. This type of statistical analysis is not my area of expertise, so I will defer to other panel members for these assessments.

I will observed just one point relative to SO signal durations and that is there should be some consideration of the probability that a SO signal will not clear (infinite duration). In the case of the dc testing in particular, there were some very long duration signals observed that I do not think should be dismissed. While most of these occurred in Penlight testing, they are, in my opinion, valid data and should be factored into the duration guidance.

There are also other factors that have not been explored in testing that could lead to SO signals being "locked-in" before they self-mitigate. In particular, disrupting the fire will disrupt the progression of damage from fully functional to fully degraded, and this disruption can occur at any point. None of the circuit failure mode tests have explored the effect of extinguishing a fire after initial cable failures occur but before full cable burn-up is observed. For example, given and external exposure fire, such as a cabinet fire, exposing overhead cables firefighting efforts will focus first on the exposure fire source (e.g., the cabinet). Once the exposure fire is suppressed, the cables will likely self-extinguish (unless a very large-scale cable fire has been allowed to develop). In this scenario, the cables may very well be left in an intermediate damage state; that is, some conductors have lost insulation integrity while others remain essentially intact, and with circuit fuses still intact.

Overall, I think the testing may not provide an accurate representation of the actual fire events in this regard, and some consideration should be given to the potential that SO signals will not self-mitigate. Nominally I would recommend a lower-bound estimate on this effect for all scenarios of 1.0E-4. That is, at a bare minimum, 1 in 10,000 spurious operation signals will have an infinite duration regardless of power source or cable configuration.