A Case Study on the Use of reverse FMEA (*r*FMEA) and the Scientific Method in a Fire Cause Determination

Kerry D. Parrott & Douglas R. Stahl, PE
Stahl Engineering & Failure Analysis, LLC
Fort Wayne, Indiana
www.Stahl-Engineering.com

EXTENDED ABSTRACT

Today the fire investigation community relies heavily on both NFPA®921: *Guide for Fire and Explosion Investigations* and NFPA®1033: *Standard for Professional Qualifications for Fire Investigator* as authoritative standards in the fire investigation profession [1]. Both of these texts, as well as other prominent fire investigation texts like *Kirk's Fire Investigation*, stress the use of the Scientific Method for determining the origin and cause of a fire or explosion.

Most fire investigators identify the Scientific Method as the correct and preferred methodology for determining origin and cause during a fire investigation; however, the application and documentation of this methodology vary significantly. Very few formalized tools exist for the practical application of the scientific method in fire investigations and those that do are rarely used or encountered in both published literature and practice [2]. Such a formal tool or procedure should assist investigators in employing critical thinking skills in order to correctly infer specific conclusions from observed data. The tool should also be systematic, intuitive, reliable, and valid. Additionally, its application should serve to document the entire process of hypothesis formulation and testing for future reference.

The authors, in cooperation with a Quality Tools expert, have previously developed and published "*r*everse Failure Modes and Effects Analysis (*r*FMEA)" as a methodology to help apply the scientific method for use in fire cause determinations [3]. That paper (*Applying Advanced FMEA Methods to Vehicle Fire Cause Determinations*) detailed the development and scientific basis of the *r*FMEA methodology. The present paper, however, will briefly overview the *r*FMEA process and concepts, specifically concentrating on the practical application of the *r*FMEA methodology through an actual case study.

We will also demonstrate how the *r*FMEA methodology meets the objective of assisting investigators in employing critical thinking skills in order to correctly infer specific conclusions from observed data. Furthermore, we discuss its systematic and intuitive nature, its validity and reliability, and its comprehensive documentation of the entire process of hypothesis formulation and testing for future reference.

KEYWORDS: fire investigation, *r*FMEA, scientific method, fire cause, reverse FMEA, failure analysis, root cause analysis

BACKGROUND and the *r*FMEA METHODOLOGY

"Failure Analysis and Analytical Tools" (Chapter 22 of NFPA® 921, 2014 Edition) refers to Failure Modes and Effects Analysis as a "technique used to identify basic sources of failure within a system" which "can help identify potential causes of a fire or explosion and can indicate where further analysis could be beneficial." NFPA® 1033 (2014 Edition) also specifies that "Failure Analysis and Analytical Tools" is one of the sixteen different topics that "the investigator shall have and maintain at a minimum an up-to-date basic knowledge... ."

Today, Failure Modes and Effects Analysis (FMEA) is one of the most widely accepted and commonly used quality tools for design (dFMEA) and process (pFMEA) (adopted particularly early in the automotive industry). Initially introduced in the 1940s by the US military, FMEA quickly gained acceptance in the growing aeronautical and aerospace fields [4] before spreading to the automotive sector and, subsequently, the associated automotive supplier sector. Today FMEA usage is gaining in the Medical, Information Technology, and Renewable Energy sectors as well. Since Ford Motor Company's early introduction of FMEA to the American automotive industry, this ever evolving tool has become a powerful technique for helping designers recognize and evaluate potential product failure modes early in the design and manufacturing processes, eliminating or reducing potential failures and their associated effects [5]. More importantly, FMEA has primarily been a design tool for improving products and processes. Currently, the Fire Protection Engineering community also utilizes FMEA techniques as the basis for qualitative Fire Risk Analysis [6].

More specifically, FMEA is a predictive engineering tool that fosters a deeper understanding of the potential causes and effects of failures in a design. FMEA also assists in the definition and prediction of the possible effects of a potential failure while still in the design phase. In this way, failure modes can be mitigated or designed out of a product before they are ever produced [7]. Risk information produced by FMEA's assignment of severity, occurrence, and detection criteria can guide and prioritize the design process. Finally, all of this FMEA information can then be tabulated for future reference and updated as new information becomes available. As such, it is a repository for product and process design and performance knowledge, acting as a foundation for continuous product and process improvement. Most products, components, and processes involved in the modern automotive industry today have evolved, in design and development, using variations of this methodology.

FMEA is primarily a predictive design process. In contrast, determining the cause of a failure that results in a fire is a reactive investigation process. Because of this, an investigative process such as a Root Cause Analysis is more appropriate for fire cause determination. Root Cause Analysis (RCA) methodology applies to a wide variety of quality tools that have historically been used to analyze failures. RCA seeks to arrive at a cause at the "root" of a failure. The root cause is the first, the base, the initiating cause, starting an undesired sequence of events. If eliminated, the root cause has no opportunity to start a causal sequence of cascading events. The root cause answers the "why" question asked in common RCA techniques such as 8-Disciplines Problem Solving, Fault Tree Analysis, Ishikawa Diagrams, Pareto Analysis, and the 5-Why methodology (favored by Toyota Motor Corporation and originally developed by Sakichi Toyoda). Every one of these different techniques presumes that for every effect, there was a prior-occurring cause [7]; hence, the commonly used phrase: "cause and effect." More recently, this relationship has been further refined for use in the FMEA process as "cause, failure, and effect." This refinement recognizes that, from a more practical and rational standpoint, every cause and effect in an RCA is also associated with an intervening failure.

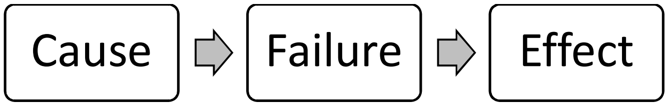


Figure 1 Cause, failure, and effect sequence

In this paper, as in general quality tool terminology, "failure" is defined as the inability to perform an intended function. This definition ensures the proper application of this methodology in order to fully determine and analyze the significant causes, failures, and effects in the critical failure process. Thus a "failure" in this analysis is not necessarily a failure defined in a legal sense, a sense that incorporates the ideas of risk, responsibility, and liability.

RCA techniques strive to determine how every effect can be traced back to its original or root cause. By applying FMEA sequencing to RCA, we can connect every effect, such as an effect observed during a vehicle fire investigation, to a failure, and connect every failure to a cause. The linear and sequential nature of these events means that every cause also has a pre-occurring cause (of the next order), until the root cause can be determined (to the order of detail required for the circumstances of the particular analysis). From a practical application approach, FMEA and RCA can be thought of as chronologically mirrored opposites. FMEA looks forward to predict how a design will perform or potentially fail and to determine the risks associated with those failures. On the other hand, RCA looks back to see what failures may have occurred during the design, manufacturing, or maintenance processes [8]. *Because these sequences are mirror opposites, we can therefore reverse the FMEA methodology to arrive at a root cause methodology,* designated as *reverse* FMEA (*r*FMEA*)*. This chronological life cycle of a vehicle system or component – through its initial design, a fire event, and the causal investigation – can be symbolically expressed as follows:

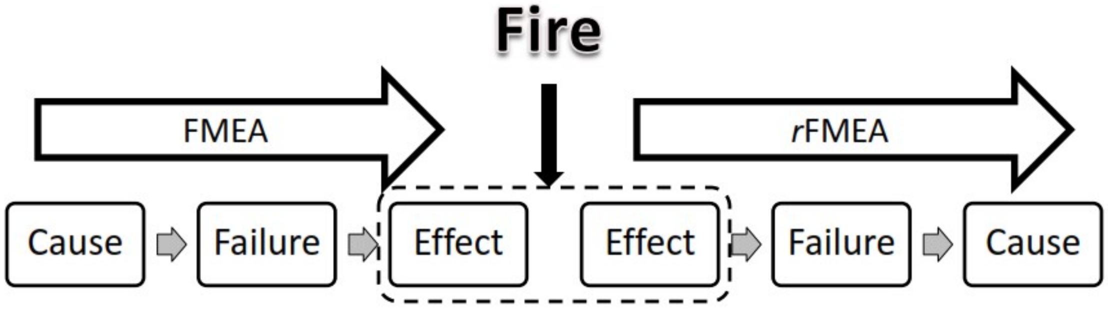


Figure 2: Chronology of a Product Fire Failure

The application of the "*reverse* FMEA" technique also allows an investigator to reference the original design and process FMEAs to determine if a possible fire cause was evaluated as an original design or process potential failure mode. Any causal information that was originally not considered or improperly assigned severity, occurrence, and/or detection criteria, can then be updated in previous FMEAs, providing real world feedback to the FMEA process for continuous product improvement at the design and process level.

A failure analysis fire investigation begins with the systematic establishment of an area or point of fire origin through traditional fire investigation tools such as witness information, fire patterns, and fire dynamics [9] (Arc Mapping is not a valid tool for determining a vehicle fire's origin) [10]. Next, the investigator determines the cause of the fire. This process requires discovering and understanding the sequence of events and factors in the product's design, manufacture, assembly, usage, maintenance, repair, and/or environmental conditions that combined in unexpected ways to produce the fire. Fire cause determination involves identifying the first fuel ignited, the ignition source, and the circumstances that resulted in the fire [11]. After determining an area or point of origin, the "*r*FMEA" approach provides a framework which sorts out the complexities of each product system and their interactions in a systematic and well documented process that drives towards a scientific determination of root cause. This method is especially useful in situations where multiple potential causes may be theorized from the determined effects and subsequent failures, complicating the root cause determination. As demonstrated in the following case study, the potential causes of the fire were narrowed down to failures in three separate electrical circuits added to the vehicle. *r*FMEA analysis helped determine which of the three potential circuits was involved in the cause of the fire. Though the entirety of the cause determination process used an *r*FMEA analysis framework, the case study highlights these final three electrical circuits for demonstrative purposes.

***r*FMEA AND THE SCIENTIFIC METHOD**

Using the Scientific Method is required for the determination a fire's cause in the investigation community, as referenced in both NFPA® 921 (Guide for Fire & Explosion Investigations) and NFPA® 1033 (Standard for Professional Qualifications for Fire Investigator). These two publications define the Scientific Method as the following 7-Step process: 1) recognize the need, 2) define the problem, 3) collect the data, 4) analyze the data, 5) develop a causal hypothesis, 6) test this hypothesis, 7) arrive at final hypothesis.

In vehicle fire cause analysis, Steps 1 and 2 are defined generally in the assignment of the fire investigation, "a vehicle fire occurred and we need to understand how and why the fire happened" and "we can proceed by conducting a fire origin and cause investigation" [12]. Therefore, we can primarily focus on Steps 3 through 7: the collection and analysis of the data, and the development and testing of all "reasonably possible" hypotheses. Eventually "impossible" hypotheses will be eliminated, moving the investigation toward the determination of all valid hypotheses and hopefully one probable fire cause.

Using the *reversed* "Effects - Failure - Cause" model described above, we will now discuss how to apply the sequence to Steps 3-7. "*r*FMEA's" first step determines the observable effects of the fire in the previously determined area or point of origin. This corresponds with Step 3, the collection of data. The process of collecting data on a fire-damaged vehicle fire consists of the notation of all the observable effects of the fire within the area or point of origin. Typical observable effects include shorted and beaded wires, ruptured hoses, broken turbocharger shafts, transmission fluid missing, cracked or broken components, etc. This information is then listed in the first column of the *r*FMEA form in Figure 2.

As noted in the introduction, every effect is associated with a failure. Therefore, the fourth step is the analysis of the observable effects and the consideration of the potential failures that could lead to the specific effect (one or more possible failures may exist for each observable effect). These effects are listed in the second column. Keep in mind that during this stage failures essentially constitute a lack of function. The function of an electrical power circuit's wiring is to convey power to an electrical component. That function could be disrupted by a short circuit related to a lack or insufficiency of insulation isolating the conductor. Related factors might include the type and thickness of the wire insulation, how it is clipped to prevent chaffing, or the environmental appropriateness of the insulating material. This emphasizes the importance of an investigator's familiarity with the design function of the components under evaluation in order to ensure an effective analysis. This step in the process corresponds to Step 4 of the scientific method: analyzing the data.

Next, the analyst must note that each failure had a cause and should consider each cause to be the immediate and pre-occurring reason for the failure. As mentioned earlier, failures can have more than one potential cause. Because of this, all potential causes must be listed with each failure to be analyzed later in order to determine its corresponding potential causes. By following this format, the methodology considers every cause that may have occurred. The cause and alternate potential causes are listed in the third column of the form in Figure 2. The next step in the methodology seeks to determine the cause of the cause (2nd order cause), then the cause of the cause of the cause (3rd order cause), and so on until the most probable root cause is found or when the analysis no longer makes sense. The causal sequences that terminate because they no longer make sense are the hypotheses that fail. The most probable root cause should become apparent after no more than the 5th order cause, according to the "5-Whys" methodology. To quote Taiichi Ohno, father of the Toyota Production System, the 5-Why method is "the basis of Toyota's scientific approach… by repeating why five times, the nature of the problem as well as its solution becomes clear" [13]. In NFPA® 921 terminology, every hypothesis is developed and evaluated, i.e. tested. Alternatively, this “Effect - Failure - Cause, Cause of Cause, etc.” logic path can be thought of as a tool to test your causal hypothesis. The hypotheses that fail will have to stop, and the hypotheses that do not fail will eventually identify the most probable root cause. This step in the procedure correlates to Steps 5-7 of the scientific method: developing and testing the hypothesis and arriving at the final hypothesis. Using NFPA® 921 terminology, the single final hypothesis remaining can be identified as the most probable root cause, provided only one hypothesis survives the testing process (it is possible for more than one hypothesis to survive the analysis). This information should be added to columns 4-7 of the form. Notably, this methodology meticulously documents all considered hypotheses for future reference.

Another significant aspect of the *r*FMEA methodology is that of hierarchical alignment. Consider it as a tool which helps to determine if events are linear succeeded causes or preceding events. This subject, though important, expands beyond the scope of this brief introduction.

CASE STUDY:
VEHICLE DESCRIPTION

The vehicle studied here is a 21-passenger bus built on a 16,000 pound gross vehicle weight rating (GVWR) cut-away van chassis. The cut-away van chassis was manufactured by a major original equipment manufacturer (OEM), while the bus body was manufactured and installed by a separate final stage manufacturer, i.e., up-fitter. At the time of the fire, the vehicle had just over 100,000 miles on the odometer and had been in service for approximately six years. The bus body featured a large passenger main entry bi-fold door on the front right side of the bus and a wheelchair lift on the rear right side. An additional battery box was mounted between the front entry door and the wheelchair lift underneath the frame. This battery box contained one additional battery and was wired in parallel with the standard chassis battery, which was located in the front right side of the engine compartment. The extra battery helped to power the chair lift. Both batteries were last replaced approximately two months prior to the fire. The vehicle’s main alternator was upsized to 200 ampere (A) rated capacity to account for the larger electrical loads and to provide sufficient current charge to both batteries.

All of the chassis electrical loads remained in the original OEM fuse boxes. The chassis manufacturer also equipped the vehicle with “customer pass thru circuits” that were available both at the main OEM fuse box, in the OEM auxiliary fuse box, and at the “B” pillar to provide convenient connection of accessories without the need to drill through the cowl and into the engine compartment to access battery power. All of the electrical system fuses for the bus body were in an additional separate fuse box installed by the up-fitter, located on the front right side of the bus interior mounted directly to the floor and just forward of the main entry door. This additional body fuse box was equipped with a battery feed terminal for convenient access to battery power, as well as an unused pre-wired, fused radio connection points to facilitate the installation of aftermarket radios.

Shortly after the bus was purchased, a 2-way radio (meant for dispatcher/driver communication) was installed by a third party, as in other exemplar buses in the fleet. This same third party was also responsible for the continued maintenance of these radios. The radio was designed to require three electrical connections; main electrical power to the radio, an ignition power sensing electrical connection, and a ground wire. All three circuits were installed with 12-gauge wiring. The radio product information specified the power circuit should have been fused at 20A and the ignition power sensing circuit at 4A. The only other electrical aftermarket modification was the installation of a windshield mounted video event recorder. This video camera was installed with three 16-gauge wire electrical connections; one fused with a 3A fuse supplying power to the camera, one circuit for ground, and one circuit fused with a 3A fuse for ignition power sensing. Ignition power sensing allowed the camera to come on only when the vehicle is running.

Inspection of exemplar units with similar 2-way radio installations by the same third party showed the radios were directly wired into the up-fitter floor mounted fuse box using fuse taps. A fuse tap is a nonconventional electrical connection of either a bare wire inserted into one of the terminals of a fuse block, or alternatively a metallic terminal that is inserted into an existing fuse. Neither is an appropriate connection as the fuse blocks are not designed to accommodate them, and their use may overstress the fuse block terminal. This bus fleet previously experienced intermittent electrical problems caused by the use of fuse taps. Additionally, a type of fuse tap is available in the automotive aftermarket that replaces a fuse directly in the fuse panel and converts one slot in the fuse box into two slots, although these are often not recommended and, according to the manufacturer of the fuse taps, should never be used for circuits exceeding 10A. Typical 2-way radios draw just under 20A.

CIRCUMSTANCES

Three days prior to the fire incident, the bus was taken out of service and the batteries were disconnected after the driver reported having electrical problems with the instrument panel lights upon returning to the transit facility. The bus was parked in the garage with the key in the "off" position, which was then stored in the main office. The next day, the bus would not start and was connected to a battery charger. The keys were returned to the main office. The battery charger was still connected to the bus at the time of the fire two days later. According to the surveillance video, the bus began to smoke from the top of the passenger door, overnight on the third day after it was parked. Approximately 20 to 30 minutes later, visible flames appeared from the top of the right side passenger door.

DETERMINATION OF ORIGIN

The complete details of the fire origin process in this investigation are outside the scope of this paper. However, it is appropriate to mention that a high degree of confidence rests in the origin of this fire as the incident was captured on a surveillance video. The video shows smoke beginning to emanate from the vehicle and then shows flames coming out of the top of the main passenger entry door. This video evidence was also consistent with the fire patterns remaining on the vehicle after the fire. These patterns were distinctive and well defined as the vehicle was parked in a building equipped with a sprinkler system that prevented the fire from spreading extensively. The fire patterns observed, the fire dynamics and materials involved, and the fuel loads available are all consistent with an origin area of the front right side bus body, just inside and forward of the main passenger entry door on the floor and upward. This is also the location of an electrical fuse panel installed by an up-fitter that supplies power to the bus body. The 2-way radio and event video recorder were wired into the bus in this spot as well.

DETERMINATION OF CAUSE

Because this paper seeks to illustrate the use of the *r*FMEA process, we will not discuss the initial fire cause analysis prior to the exclusion of all potential fire causes other than electrical causes within the determined area of fire origin. The complete analysis followed the *r*FMEA process framework but is not included in order to focus on the limited demonstrative examination of the final fire cause analysis.

Three primary "observable electrical effects" were found and identified in the previously determined area of fire origin. These three observable effects generated sixteen potential causal hypotheses which, through the *r*FMEA process, were narrowed down to just one probable cause. These three observable effects are as follows:

The first (1) was a short section of a 12-gauge electrical circuit added to a maxi fuse block which ended in a metal globule. This maxi fuse connection is normally unused (based on an inspection of similar exemplar buses) and is connected directly to the battery at all times, even with the ignition off. This circuit was connected to the maxi fuse block using a flag connector crimped to a 12-gauge wire. There were only 5¼ inches of wire found remaining with the flag connector and a metal globule at the end of the wire. The metal globule is a possible indication of beading from an electrical short circuit or may also simply be caused by the ambient melting of the wire. The analysis and determination of the globule's creation will proceed out of the *r*FMEA process later. There was no evidence found that this circuit was fused and it was determined to be the main power circuit to the 2-way radio due to its direct connection to battery power.

The second effect (2) was another short section of a 12-gauge electrical circuit added to a mini fuse block that also ended in a metal globule. This circuit was added using a fuse tap to the power side of the mini fuse block at a connection that normally fuses the dome light in the bus (based on a fuse panel diagram from the up-fitter). This circuit is only powered when the ignition key is on. No evidence suggests that this circuit was fused. Since this circuit is powered only when the ignition is on, this was determined to be the 4A ignition power signal connection for the 2-way radio. There were 8¾ inches of wire found remaining with the fuse tap. The wire ended in a metal globule in what could, at this point in the analysis, be interpreted as the aforementioned melting or beading.

The third (3) was a section of a 16-gauge electrical circuit connected directly to the positive battery terminal of the fuse panel. This electrical junction is always powered. This circuit was protected by a 3A in-line fuse and was determined to be the electrical power for a front-facing digital event camera, based on the sizes of the wire and fuse. The end of this wire also ended in a metal globule, similar to the other two wires.

All three electrical circuits with observable effects ended in separate metal globules, which could be interpreted as either melting or beading, depending on the skill of the investigator and the extent and depth of the analysis. Through use of the *r*FMEA methodology, further interpretation or analysis of the metal globules at the end of the circuits was determined, in this case, to be unnecessary for identifying the root cause. This process of elimination provided a more reliable root cause determination that did not depend on conflicting current controversial theories of the analysis of such globules.

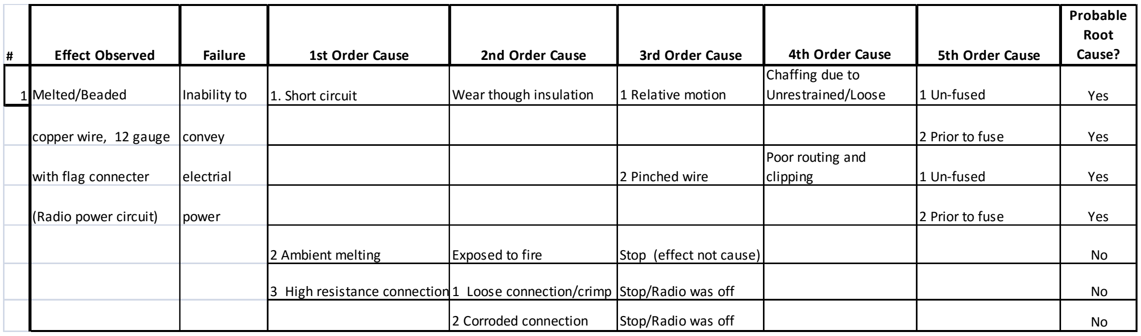
We also know that there were no other electrical modifications made to this vehicle. We can therefore determine that the two 12-gauge electrical circuits ending in melted globules were electrical power circuits to the 2-way radio, as noted above. This is based on the fact that the wires were: a) the correct gauge, b) larger than 16-gauge wires used by the video event camera, and c) connected to the fuse panel like the radio installations in other exemplar vehicles inspected. The ground circuits for both the 2-way radio and video camera were unremarkable and later determined to be uninvolved.

***r*FMEA ANALYSIS**

The *r*FMEA analysis process starts by identifying each of these observable effects on a spreadsheet. The first effect described above is the beaded 12-gauge wire connected to the fuse box with a flag connector, listed in the table in Figure 3 below. The next *r*FMEA analysis step determines the failure associated with this effect. All three significant observable effects involved electrical power wires that ended in a metal globule. As noted previously, a "failure" is generally defined as the inability to perform an intended function. Thus in this analysis, the failure associated with each of the three electrical power circuits could be described as the wire's "Inability to Convey Electrical Power."

The *r*FMEA analysis then proceeds with the determination of potential causes for each failure. Without the need for further study of the metal globules at the end of each wire, each possible cause for the similar failures can be listed for each wire, as shown in Figure 3. Potential causes for each failure were determined to be: an electrical short circuit, ambient melting of the wire and high resistance connections – all which could produce a metal globule at the end of an unconnected electrical power wire. All of these cause options are considered as a potential first order causes.

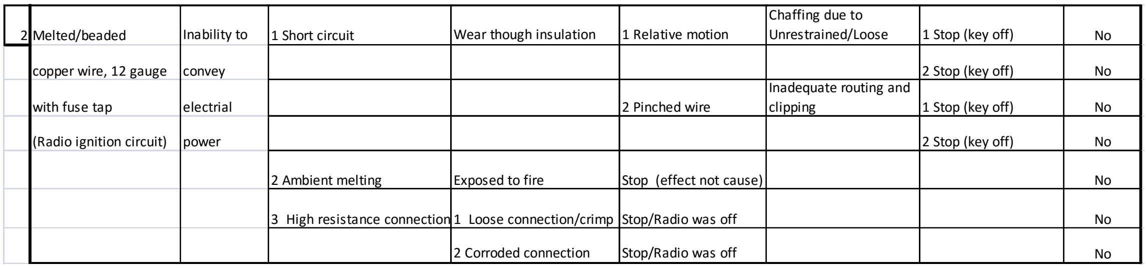
Next, we continue the cause-failure-effect model and consider all of the different reasons why the circuit could have shorted, experienced ambient melting, or experienced a high resistance connection. As illustrated in Figure 3, a short circuit occurs when the insulation on a wire is worn through and allows a connection to ground. Insulation can wear through due to either relative motion allowing for the insulation to chafe, or because the wire was pinched during installation. In all of these cases, this circuit may or may not have been fused. Even if the circuit was fused, it is possible for the short circuit to occur on the power side of (wire prior to) the fuse, negating the protection afforded by the fuse. If this wire melted due to the ambient temperatures in the fire instead of shorting, then that must logically have been an effect of the fire and not a cause, allowing us to cease this analysis. If we consider the possibility that the radio was off at the time of the fire, a high resistance connection could not have been a cause since no current was being drawn through the circuit. When this matrix of options is expanded, we end up with seven hypotheses for why this wire show signs of beading or melting. The three hypotheses associated with melting and a high resistance connection can be ruled out. The four remaining hypotheses all support an electrical short circuit. The only question that cannot be answered is whether the root cause was an “un-fused” installation of this circuit, or if the short circuit occurred because the fuse was installed too far away from the source of power. Responsibility in both cases falls on the third party installer/maintainer.



#	Effect Observed	Failure	1st Order Cause	2nd Order Cause	3rd Order Cause	4th Order Cause	5th Order Cause	Probable Root Cause?
1	Melted/Beaded	Inability to	1. Short circuit	Wear though insulation	1 Relative motion	Chaffing due to Unrestrained/Loose	1 Un-fused	Yes
	copper wire, 12 gauge	convey					2 Prior to fuse	Yes
	with flag connecter	electrial			2 Pinched wire	Poor routing and clipping	1 Un-fused	Yes
	(Radio power circuit)	power					2 Prior to fuse	Yes
			2 Ambient melting	Exposed to fire	Stop (effect not cause)			No
			3 High resistance connection	1 Loose connection/crimp	Stop/Radio was off			No
				2 Corroded connection	Stop/Radio was off			No

Figure 3-rFMEA First Observable Effect

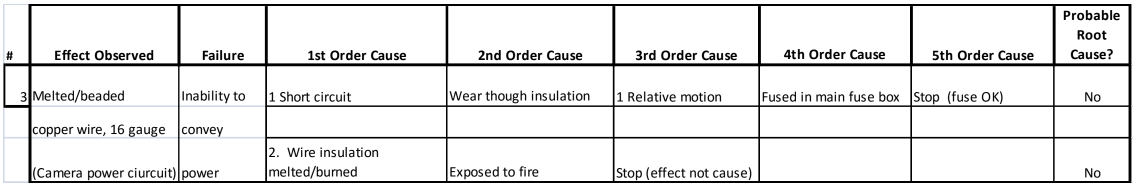
The second observable effect was a 12-gauge wire ending in a globule installed with a fuse tap to a circuit that is only electrically powered when the key is in either the “run” or “accessory” position. Therefore, the analysis is identical to the one above and generated seven more hypotheses. However, the potential cause analysis stops because the key was in the “off” position and the circuit had no power. This effect then cannot be linked to a probable cause of the fire as shown in Figure 4.



2	Melted/beaded	Inability to	1 Short circuit	Wear though insulation	1 Relative motion	Chaffing due to Unrestrained/Loose	1 Stop (key off)	No
	copper wire, 12 gauge	convey					2 Stop (key off)	No
	with fuse tap	electrial			2 Pinched wire	Inadequate routing and clipping	1 Stop (key off)	No
	(Radio ignition circuit)	power					2 Stop (key off)	No
			2 Ambient melting	Exposed to fire	Stop (effect not cause)			No
			3 High resistance connection	1 Loose connection/crimp	Stop/Radio was off			No
				2 Corroded connection	Stop/Radio was off			No

Figure 4- rFMEA Second Observable Effect

The third observable effect becomes an abbreviated version of the analysis presented above and only generated two more potential hypotheses. The logical potential causal sequence stops since the circuit was properly fused for this application as shown in Figure 5.



#	Effect Observed	Failure	1st Order Cause	2nd Order Cause	3rd Order Cause	4th Order Cause	5th Order Cause	Probable Root Cause?
3	Melted/beaded	Inability to	1 Short circuit	Wear though insulation	1 Relative motion	Fused in main fuse box	Stop (fuse OK)	No
	copper wire, 16 gauge	convey						
	(Camera power ciurcuit)	power	2. Wire insulation melted/burned	Exposed to fire	Stop (effect not cause)			No

Figure 5- rFMEA Third Observable Effect

The *r*FMEA analyses for each of the three individual effects are combined in Figure 6 providing a concise documentation of the scientific method analysis leading to a probable root cause for this fire that satisfies the requirements and purposes previously noted for both NFPA®921and NFPA®1033.

#	Effect Observed	Failure	1st Order Cause	2nd Order Cause	3rd Order Cause	4th Order Cause	5th Order Cause	Probable Root Cause?
1	Melted/Beaded	Inability to	1. Short circuit	Wear though insulation	1 Relative motion	Chaffing due to Unrestrained/Loose	1 Un-fused	Yes
	copper wire, 12 gauge	convey					2 Prior to fuse	Yes
	with flag connecter	electrial			2 Pinched wire	Poor routing and clipping	1 Un-fused	Yes
	(Radio power circuit)	power					2 Prior to fuse	Yes
			2 Ambient melting	Exposed to fire	Stop (effect not cause)			No
			3 High resistance connection	1 Loose connection/crimp	Stop/Radio was off			No
				2 Corroded connection	Stop/Radio was off			No
#	Effect Observed	Failure	1st Order Cause	2nd Order Cause	3rd Order Cause	4th Order Cause	5th Order Cause	Probable Root Cause?
2	Melted/beaded	Inability to	1 Short circuit	Wear though insulation	1 Relative motion	Chaffing due to Unrestrained/Loose	1 Stop (key off)	No
	copper wire, 12 gauge	convey					2 Stop (key off)	No
	with fuse tap	electrial			2 Pinched wire	Inadequate routing and clipping	1 Stop (key off)	No
	(Radio ignition circuit)	power					2 Stop (key off)	No
			2 Ambient melting	Exposed to fire	Stop (effect not cause)			No
			3 High resistance connection	1 Loose connection/crimp	Stop/Radio was off			No
				2 Corroded connection	Stop/Radio was off			No
#	Effect Observed	Failure	1st Order Cause	2nd Order Cause	3rd Order Cause	4th Order Cause	5th Order Cause	Probable Root Cause?
3	Melted/beaded	Inability to	1 Short circuit	Wear though insulation	1 Relative motion	Fused in main fuse box	Stop (fuse OK)	No
	copper wire, 16 gauge	convey						
	(Camera power ciurcuit)	power	2. Wire insulation melted/burned	Exposed to fire	Stop (effect not cause)			No

Figure 6- Complete rFMEA

CONCLUSIONS

The fire cause investigation conclusion derived from this analysis is the probable cause of this fire was a short circuit in the main electrical power feed to the 2-way radio. This short circuit occurred either because the circuit was not fused or because the short circuit occurred prior to the possible fuse installation location. A short circuit in the un-fused radio power circuit would overheat the wire, causing the wire insulation to burn. This indicates the wire insulation was the first fuel ignited. Once the wire insulation starts to burn, the fire spreads to the other plastic components in the fuse box, including the fuse box cover, and then to other parts of the bus body, consistent with the fire dynamics and video witness information.

We reached this conclusion after evaluating sixteen different possible hypotheses derived from just three observable effects. Tabulating these different hypotheses in cause-failure-effect order helps ensure that all reasonable options for each failure are considered. This tabulation also assists the investigator in their attempt to easily identify which of the possible causes are not consistent with the circumstances of the fire and the possible cause(s) that are consistent with the fire evidence. Any hypotheses that are consistent with the fire evidence are the final hypotheses, or the determined root cause(s), depending on your preferred terminology. Any new information or data that is collected at a later time can also be easily added to the tabulation to see if the results change.

The goals for this *r*FMEA analysis process were to help correctly infer specific conclusions from the observed data, to be both systematic and easy to understand, and to be reliable and valid. It should also document the entire process from gathering data to hypothesis formulation and hypothesis testing. All of these objectives have been met while strictly adhering to the Scientific Method as described by NFPA® 921. This example is very simple and straight forward and the same conclusions could have been derived without the use of the *r*FMEA methodology; however, this example was chosen specifically because it is simple, allowing for an emphasis on the process instead of getting lost in the details of a more complex investigation.

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