Lesson Learned

Root-Cause Analysis Tools – Events and Causal Factors Charting

Primary Interest Groups
Generator Operators (GOP)
Generator Owners (GO)
Transmission Operators (TOP)
Transmission Owners (TO)
Reliability Coordinators (RC)
Balancing Authorities (BA)

*Note: This is a topical Lesson Learned. In this case, the objective is to provide information on a root-cause methodology more than to discuss a specific event. This is the third in a series of U.S. Department of Energy (DOE) root-cause analysis methodologies provided in NERC Lessons Learned that are simple in concept and powerful in use. Events and causal factors charting (ECFC) incorporates a sequence of events with the outputs of change analysis and barrier analysis in an easily understood format that can be used in management presentations. Like the prior LL20210201 RCA Tools – Change Analysis, and LL20210201 RCA Tools – Barrier Analysis, this Lesson Learned includes a case study with an example chart (see **Figure 2**) and a user's "how-to" guide (See **Attachment 1**).*

Example Scenario:
A phase B to ground fault occurred on a 230 kV line and was expected to be cleared instantaneously at both line ends by zone 1 protection settings. However, technicians left open a test switch, which disabled relaying at one end, preventing a breaker from operating for the fault and causing all four 230 kV lines leading into the breaker's station to trip open.

Details
As shown in **Figure 1Figure 1**, all four 230 kV lines leading into Station A tripped open at remote ends, and there were no operations at Station A to indicate the cause of this event. A breaker at Station B reclosed with no issues, powering Station A back up immediately. The transmission operations center (TOC) then closed the breaker at Station C, putting the Station A to Station C 230 kV line back in service. The TOC closed Station D breaker 9018 and had the plant close breaker 9015, putting the Station D–Station A 230 kV line back in service. Operations contacted the interconnecting entity that owned the Station E OCB 1, GCB 5, and GCB 8 breakers that tripped. The operator on the desk reported that the breakers were not showing any trips. Two breakers at Station F tripped as well. Operations closed Station F breakers 8761 and 8777, putting the Station F to Station G 138 kV line back in service.

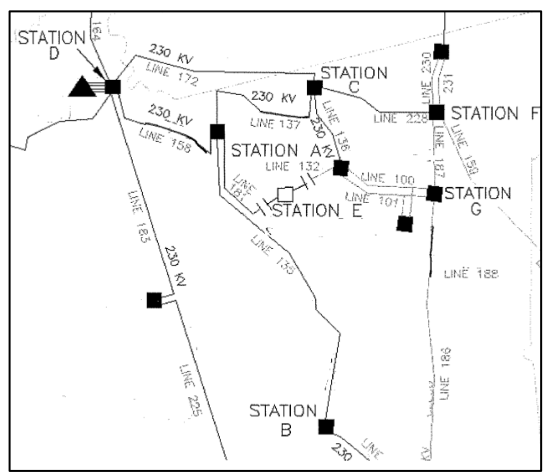

Figure 1: Map of Stations Involved

The investigation revealed that the Station A protection system trips for the Station A to Station B line were opened to facilitate testing of the newly replaced Station A breaker 9105. However, the testing was not completed on Friday and the protection isolation switches were left open over the weekend.

An events and causal factors chart (see **Figure 2**) was constructed to aid in determining causes and potential corrective actions. The chart led to several observations, as follows:

- No design engineer was on site during the commissioning of a breaker at the substation to track the status of work, consult on/approve changes to the plan or equipment due to unexpected conditions, or analyze the risk of leaving protection disabled and ensure adequate communication with operations.
- A relay technician supporting breaker commissioning tests made a field change without properly communicating it and left for the weekend, leaving a line without proper protection.
- Operators failed to ensure adequate communication with the relay technician regarding equipment status, specifically what protection equipment was going to be taken out of service to support testing and the nature of the as-left status when the technician stopped work for the weekend (protection left out of service).

Entity Corrective Actions

- Work with construction engineering to ensure that a design engineer is available to work in the field with relay technicians during commissioning.
- Create a learning from incident (LFI) for this event and share with electric system maintenance (ESM) groups and operations.
- Improve communication between operations and field personnel on status of protection equipment prior to exiting a substation.

Lesson Learned

Commissioning work requires careful planning, coordination, and communication between multiple parties.

- Field changes should not be unilateral decisions—communication between technicians, engineering, and operations allows the best options to be selected and ensures that as-left status is known.
- If planned work cannot proceed safely or does not support reliability and no support (engineering, operations, supervision) is available, equipment should be placed in a safe condition and work stopped while the needed support is contacted. Do not proceed in the face of uncertainty.
- Engineering presence in the field during commissioning can communicate/consult with others to adjust plans when unexpected conditions are encountered as well as track and document the work. They can also provide peer-checking for technicians prior to critical actions and monitor results.
- Operations must insist on communication of equipment status changes, including modifications to protection

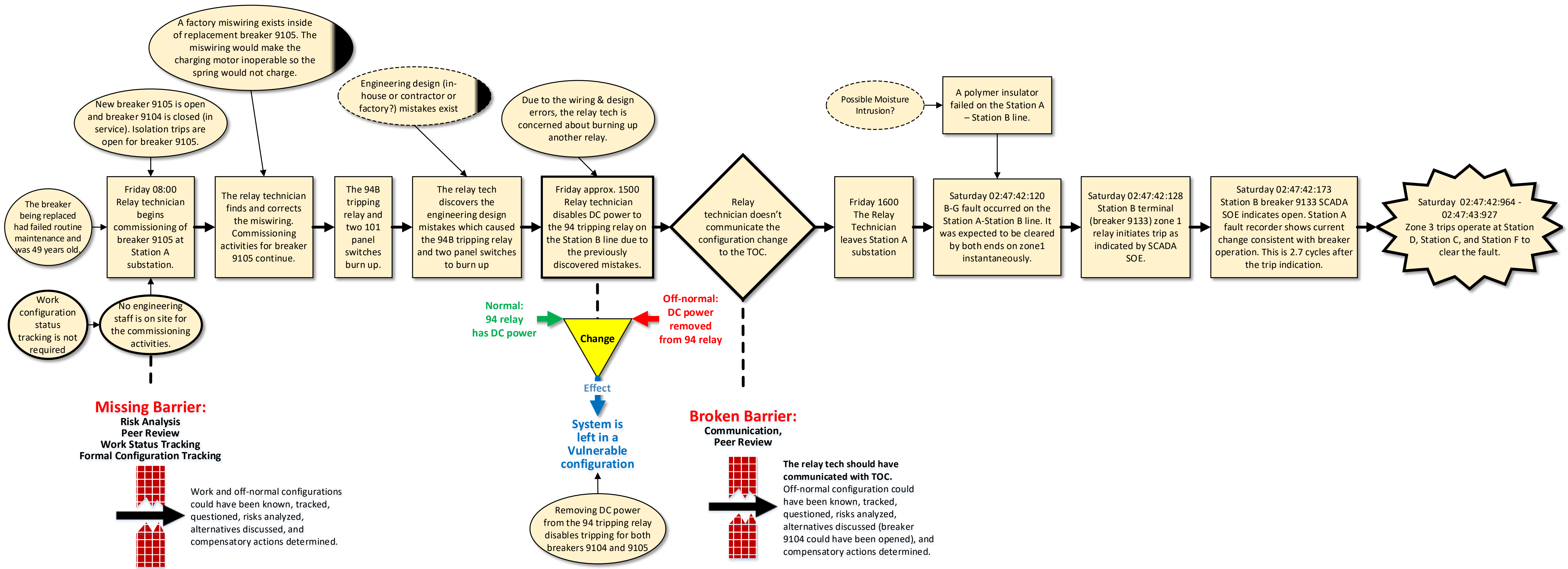

Figure 2: Events and Causal Factors Chart

NERC’s goal with publishing lessons learned is to provide industry with technical and understandable information that helps them maintain the reliability of the bulk power system. NERC is asking entities that have acted on this lesson learned to respond to the short survey provided in the link below.

Click here for: Lesson Learned Survey

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For more Information please contact:

NERC – Lessons Learned (via email)

This document is designed to convey lessons learned from NERC’s various activities. It is not intended to establish new requirements under NERC’s Reliability Standards or to modify the requirements in any existing Reliability Standards. Compliance will continue to be determined based on language in the NERC Reliability Standards as they may be amended from time to time. Implementation of this lesson learned is not a substitute for compliance with requirements in NERC’s Reliability Standards.

Additional Reference Material

Attachment 1: Root Cause Analysis Tools – Events and Causal Factors Charting

Excel File: Template for change analysis, barrier analysis, and events and causal factors charting

Attachment 1

Root Cause Analysis Tools – Events and Causal Factors Charting

Major events are usually not the result of a single failure but of complex conditions that have developed over time and may have transpired because of interactions between multiple people, organizations, systems, tasks, environments, and/or components. Barrier and change analysis are quality tools that anyone can use but are inadequate to clearly show a sequence of events (SOE). Even simple SOE charts can reveal gaps in logic and help prevent inaccurate conclusions.

Events and causal factors charting (ECFC) is an excellent root-cause analysis tool for examining the sequence of events and causes leading up to an event. It is more complex and work-intensive than a barrier or change analysis and should be conducted under a team formed to work on it. It's product—a chart that "tells the story"—and excellent for explaining complex events. During development, the chart helps ensure that the investigation proceeds smoothly, that gaps in information are identified, and that the investigators have a clear representation of event chronology for use in evidence collection and witness interviewing.

The Department of Energy (which uses ECF as the abbreviation) describes a formal ECFC method in Section 2.6.3 of DOE-HDBK-1208-2012 Volume I, Accident and Operational Safety Analysis, Volume I, Accident Analysis Techniques.

Some easier-to-follow guidance is available in *Events & Causal Factors Analysis* written by Scientech, Inc. for the DOE (SCIE-DOE-01-TRAC-14-95) in August 1995. Their legacy example chart is still recycled by some contract root-cause analysis trainers.

The Noordwijk Risk Initiative Foundation in the Netherlands has "ECFA+" is a version of ECFC that uses specially printed event and condition Post-It forms though its guidance can be used for any ECFC. A Visio Stencil of the foundation's special event and condition forms is available for download from this page and can be used to construct the chart in Visio.

Creating the Chart

You can use any of the three formal guidance documents above or follow the simplified method below.

First, obtain from management (or develop from the investigative team) a scope and charter. The scope should include a problem statement describing the adverse event (what and when) that is being analyzed along with the consequences of the event that needs to be prevented from recurring (as the reason for a root-cause investigation and the basis for expending time and effort on the analysis and corrective actions is to prevent recurrence). The charter needs to identify the management sponsor and the investigative team's membership, specify resources to be made available, describe authority to request pertinent evidence/documents/interviews, and detail the expected report output form (the deliverable) and the expected duration of the investigation.

Next, the terminal event (the adverse event defined in the scope) that you are analyzing should be identified. Usually, the terminal event (some references call it the "primary effect") will mark the end of your chart unless you are also examining the response to the event. In the case of major events, always expect the quality of the response to be examined for improvement opportunities.

You'll need to collect all available SOE information (including logs, recordings, completed checklists, eyewitness descriptions, and interviews) and plenty of space—real or virtual. You'll be writing text inside rectangles, ovals, and diamonds and connecting them with lines and arrows. The product will be much longer than tall and not fit on standard letter-size paper. Use a vector-based drawing program like Microsoft Visio or an Excel worksheet or use old-style "Sticky Notes" and markers on a long roll of butcher paper laid out on a table or attached to a wall.

Events are normally represented by rectangles and conditions by ovals. The terminal event will be a specially highlighted shape like a star or explosion shape with thicker borders (see **Figure A1**).

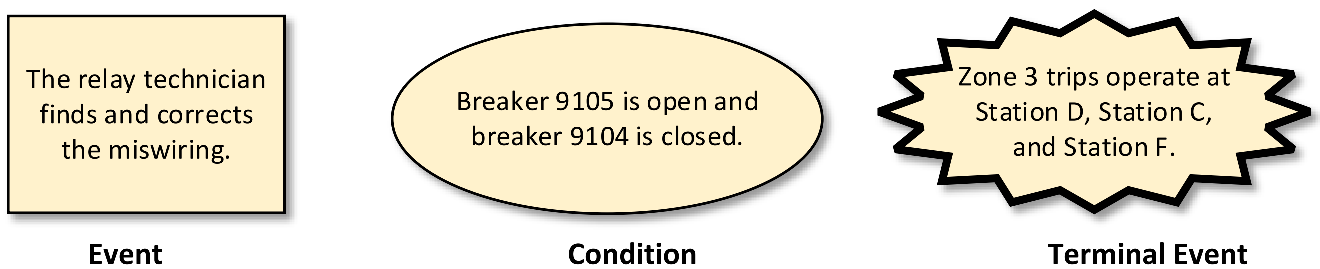


Figure A1: Standard Events and Causal Factors Chart Shapes

Inside each shape, describe the event or condition that it represents with a succinct sentence. Different shape colors and border thicknesses may be used to differentiate between events and conditions and whether they are on the main sequence or a sideline. This choice is up to the investigation team, but make sure to be consistent and, for legibility, use high contrast between shapes' colors and the text they contain.

Events should be connected by thick arrows. The "primary event line" is where the main sequence of events is laid out left to right (unlike the similarly named "cause and effect charting")[1] along the center of the chart and is linked by the thickest/boldest arrows (see **Figure 2**).

Secondary event sequences, simultaneous events in different locations, contributing factors, and systemic factors should be depicted less boldly on horizontal lines at different levels above or below the primary sequence and connected with thinner lines/arrows.

Events should track in logical progression from the beginning to the end and include all pertinent occurrences. Do not exclude any information during the evidence-gathering phase unless it is clearly

[1] There are several very good logic tree root-cause analysis tools that are descendants from the Ishakawa "Fish Bone" method, which was traditionally read right to left like Japanese, and they often keep that convention at the cost of confusing the uninitiated Westerner. The ECFC method is easier for European language readers (left to right) to immediately understand without much explanation.

unrelated to the event sequence and formative conditions. After the ECFC is fully populated and the information vetted, you can trim out irrelevant items.

In the case of major events, start with the main adverse event nearer the middle of the page and work out from it in both directions to show the pre-event causal factors and the organization's post-event response, which may also be studied for improvement opportunities.

Identify causal factors and inappropriate actions—those events that should not have occurred and were essential to the development of the adverse event—and format them differently than the regular events (color, shape, etc.). If eliminating an event or inappropriate action would have prevented the adverse event, it is a candidate for a "root cause." Traditionally, a root-cause "yellow sticky" would be turned 45° to make it a "diamond" to call attention to it.

One standard method for highlighting a condition that was a causal factor is to color in an end of its oval. Coloring the end of an oval is easy with a marker on paper. However, some computer drawing tools make it difficult to color in one end, so other formatting like background fill color choices is also commonly used to call attention to causal factors.

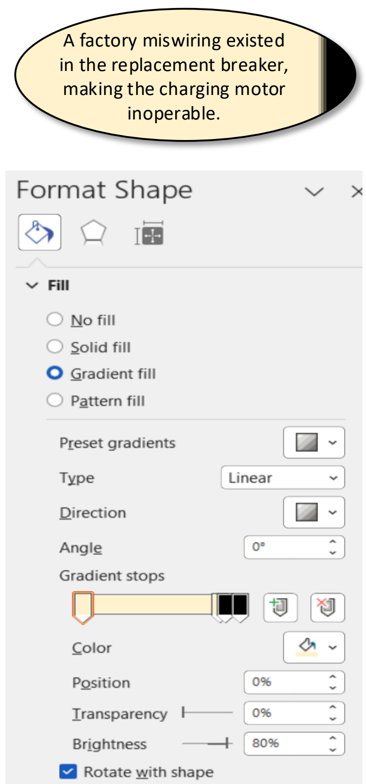


Figure A2: Shading One End of an Oval

Microsoft Word, Visio, and Excel can shade one end of an oval or other shape if the user tinkers with a four-stop gradient fill (see **Figure A2**). Gradient fill does not come with four stops by default—the user must click inside the slider to create a new one. Two of the gradient stops—a black one and a yellowish one—in the slider are almost but not quite on top of each other. The outer end stops are set with one end black and the other yellowish (how the oval above was set up). Clicking on a slider selects it so the user can set its position and color.

ECFCs assist in examining the completeness of the investigation and the logic used. Holes in either during the development of the chart can help guide additional evidence collection and analysis needs. Each event and condition must be based upon valid factual evidence. If they do not logically connect and follow from one to the next (How did this thing get mispositioned? What information was used for decision making? Why was that step skipped? etc.), there may be missing information. Gather the additional facts necessary to thoroughly explain the terminal event, answer questions that arise from chart construction, and ensure that there are no other viable potential causes that could explain the terminal event.

Using a Formal Evidence Matrix

It is often helpful to draw up an evidence matrix—a table—to match the ECFC elements to the evidence collected (see **Table A1**). Write down summaries and descriptions of the evidence—measurements, observations, tests, photographs, sources, etc. Add dates and times for events where known. The date and time that a condition was first observed and, if known, the duration

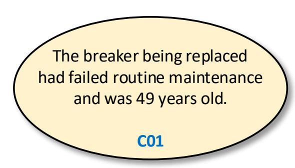


Figure A3: Key # C01 in a Condition Oval

of a condition may also be useful. Include a column with an alphanumeric key code and put the key code inside the corresponding shape on the chart (see **Figure A3**). The keys use "E" for Event or "C" for Condition and a unique identifying number, usually sequential. The more complex and lengthier an ECFC is, the more valuable an evidence matrix will be in keeping organized and answering the inevitable "How did you know this?" or "Why wasn't it this?" questions. The evidence matrix is a tool for the investigators and not commonly found in reports but may be included as an appendix, depending on management direction (and how data-hungry the report recipient may be). If you are called to be an expert witness in a legal case and use an ECFC, an evidence matrix is an absolute must.

Table A1: Sample Evidence Matrix

Key #	Shape Text	Date/Time	Evidence, Details, Comments
C01	The breaker being replaced had failed routine maintenance and was 49 years old.	Prior to E01	Breaker 9105 maintenance history
C02	New breaker 9105 is open and breaker 9104 is closed	Prior to E01	Thursday Station A equipment status record
E01	Relay technician begins commissioning of breaker 9105 at Station A substation.	Friday 0800	Work Order 4560123
E02	The relay technician finds and corrects the miswiring.	Friday ≈0900	Work Order 4560123

If a hole exists in the sequence of events that requires an assumption, it needs to be clearly indicated as theorized/presumptive by dotted/dashed-line rectangles and ovals (or "clouds") and question marks (see **Figure A4**). Presumptive items are speculative and can degrade the reliability of the ECFC. As such, they need to be as few as possible and thoroughly vetted (meaning search for data to refute/support each of them to eliminate them or change them into fact). They should be left as presumptive only, if necessary, by logic. Put a red "BOLO" ("Be on the Lookout" for) in the evidence matrix comment column for those items and pursue what information is available to resolve it. The finished ECFC is supposed to represent what happened, not what we supposed happened or alternate possibilities.

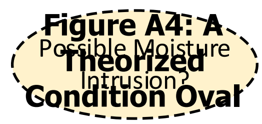


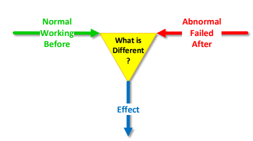
Figure A4: A Theorized Condition Oval

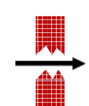
Using Change and Barrier Analysis with ECFC

The output of other root-cause analysis tools can be added into an ECFC. It is very common to see change and barrier analysis results folded into an ECFC. Using this analysis in combination with an ECFC overcomes the lack of sequence of events in those tools while adding the perspectives of those methods to your chart.

See previous NERC Lessons Learned:

- LL20210201 "Root Cause Analysis Tools - Change Analysis,"
- LL20210202 "Root Cause Analysis Tools - Barrier Analysis"





Identifying a Root Cause Using Events and Causal Factors Charting

When you are developing an ECFC, the logical interrelation between causes and effects should be made clear. Adverse events—equipment failures, human error, process failures, etc.—are the effects of some cause (contributing or root cause) and those causes will be related to factors including system conditions, design, organization and procedure factors, and human performance. Follow the processes discussed above to make sure that the chart contains enough detail to start determining the cause-and-effect relations.

Basically, for each condition (effect) identified, we should be able to determine why it occurred (cause). The root cause(s) of an event can be determined by examining the cause-and-effect relationships that led to the undesired event. For example, “the bushing had a crack” is a statement of a condition (effect); determining why “the bushing had a crack” might lead to the cause of the condition, such as “vehicular impact”—an event, which in turn requires further investigation of why it happened to get closer to a root cause (condition or event).

Steps for methodically examining the ECFC:

1. Examine the event or condition that immediately precedes the terminal event. Evaluate its significance in the cause-and-effect sequence by asking: “If this event had not occurred, or if this condition was not present, would the terminal event have occurred anyway?”
    a. If the answer is yes, then that event or condition is apparently not causal. Note your finding and reasoning in the evidence matrix. Proceed to the next prior event in the chart, working backward from the accident.
    b. If the answer is no, then determine whether the event represented normal activities with the expected consequences. If the event was intended and had the expected outcomes, then it is not significant. However, if the event deviated from what was intended or had unwanted

consequences, then it is a significant event. Note your finding and reasoning in the evidence matrix.

c. Continue working your way back through the chart to its beginning, updating the evidence matrix as you go.

2. Now go through those events and conditions associated with each significant event by asking a series of questions about this event chain, such as:

   a. Why did this event happen?

   b. What events and conditions led to the occurrence of the event?

   c. What procedures control the process involved?

   d. Are the instructions adequate? Were they followed?

   e. Was the worker qualification and preparation process adequate? Was it followed?

   f. Was the pre-job brief adequate? Were its cautions and instructions followed?

   g. What went wrong that allowed the event to occur?

   h. Why did these conditions exist?

   i. How did these conditions originate?

   j. Who had responsibility for the conditions?

   k. Are there any relationships between what went wrong in this event chain and other events or conditions in the accident sequence?

   l. Is the significant event linked to other events or conditions that may indicate a more general or larger deficiency?

The significant events, and the events and conditions that allowed the significant events to occur, are the accident's causal factors and may point to contributing or root causes.

There is also an "art" to determining what to declare a root cause. Use the cause-and-effect relationships between the various conditions and events in the chart to determine what led to the "terminal event." When you have several choices of causal factors and inappropriate actions where you could apply a corrective action to break a chain of events and prevent an event, some commonsense rules need to be applied.

First, look at a couple of definitions:

- A root cause is a fundamental cause that, if by itself were corrected, would have prevented the event.
- A contributing cause is a cause that, if corrected, would not by itself prevent recurrence of the event but may be important enough to address for the purpose of improving conditions, reducing event

consequences, or reducing probability of other events (different from the event under investigation).

There may be several places in your ECFC's sequence of events where you could intervene and prevent the terminal event, so there can be more than one root cause identified for an event. However, the number of root causes identified by successful investigators is usually few—often three or less. A low number of root causes is often one sign that the analysis has been thorough and disciplined.

You can perform a check on the thoroughness of the analysis by determining whether the potential root causes are correctable at reasonable cost and the potential correction methods do not add to your problems.

- If the identified cause is beyond the ability of management to control, then it cannot be corrected, and you need to look elsewhere. Try examining the conditions and events further upstream for something on which management does have a handle.
- In some contexts, such as regulator's viewpoint or safety, costs are not always considered. However, in a real-world business, costs must be considered. If a cause can only be corrected at a cost that is greater than living with the problem (infrequent cheap lightbulb failures, for example), then correction is unlikely.
- If the cause is not correctable, or the cost is too high, work further back in the sequence of events or in more detail to see if there is a cause that can be cured at reasonable cost. Try examining "conditions" as effects that have earlier causes and add those to your chart and analysis.
- Sometimes the cause will only be under the control of and correctable by a manufacturer, vendor, contractor, or regulator—get as much evidence as you can, build the logical case, and take that to your management, who will determine whether to pursue the item through other means, such as legal or contract efforts.

- The popular doctor's motto, "First, do no harm,"[2] should apply to root-cause investigators. When determining a cause and corrective action recommendations, be sure to avoid introducing a new problem or increasing the likelihood or severity of another existing one.

Contributing causes may be more numerous than root causes. Keep in mind that problem solving must be targeted and practical and should not be overly broad; don't allow the investigation to balloon beyond your defined scope or it will fail. Much of the same common sense (and sometimes management direction) needs to be applied to the number and level of corrective actions associated with these.

Final Report Tips

Make a short executive summary chart and use it in presenting the root-cause analysis results to management. The summary chart needs to be concise and easy to follow, preferably fitting on a single PowerPoint slide while remaining legible. It needs to show the logic essential to explaining the cause(s) of

[2] In case you are wondering: The Hippocratic Oath does not state "First, do no harm." The phrase appears to have been distilled from the Hippocratic Corpus, which includes "…have two special objects in view with regard to disease, namely, to do good or to do no harm."

the terminal event and any other important features that management will need to know while excluding extraneous details.

Showing a clear and logical development of the events and causal factors will facilitate agreement among report reviewers on the causes and minimize negative reaction from persons and organizations whose performance deficiencies may have contributed to the occurrence. They may not like what the report says, but they will know that it is fair and accurate.

It is common to find a simplified ECFC in a root-cause report. The larger working chart may contain a lot of detail that was gathered while shaping and directing the investigation that was not required to explain the event in the final investigation report. Many details may be found to not contribute to the understanding of the event and may be easily trimmed from the chart. The original detailed chart and its evidence matrix may be included as a report appendix if management wants the detail preserved.