Investigating Investigation Methodologies

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Abstract

Recent years have seen an increase in the number of investigation methodologies. For example, today investigators can choose among investigation methodologies like ICAO, ISIM. MES, Root Cause Analysis, Tripod-Beta, or TOR, to name a few. How do investigations and work products produced with these investigation methodologies compare?

Several investigators have reported comparisons of investigation methodologies but criteria for comparison, developed in different ways, have been inconsistent, leaving the question of their comparative merits unresolved. This paper is a progress report of an inquiry to develop a comparison based on a desktop simulation of an investigation with one methodology using data from a published accident report prepared with another methodology. The work is disclosing substantial differences attributable to methodologies.

Introduction

Choosing a methodology is a key investigation program decision. What information is available to support this decision? A recent paper by Sklet [1] presents a comparison of 14 different methods of investigation, offering seven different characteristics by which the methods are compared. Harvey [2] examined four accident investigation models in terms of their ability to satisfy five evaluation criteria representing his view of major purposes of accident investigation. The author [3] ranked 17 investigation models used by governmental organizations, using twelve assessment criteria. Henderson et al [4] reported five criteria for "good investigations." The Center for Chemical Process Safety [5] published a list of 18 investigation "techniques" with three basic criteria. The criteria for the these comparisons were all different.

Sklet developed seven characteristics for his comparison, derived from his expectations of the results required, and presented a table summarizing the attributes of each method of investigation to help distinguish the differences and, by implication, the relative merit of the methodologies. Harvey's criteria for comparing the four general investigation models were derived from purposes of accident investigations. He judges one model the best. In an earlier ranking of accident investigation models Benner suggested 10 criteria for judging the merits of investigation models of 17 organizations, derived from investigation objectives; statutory mandates; organizations' accident investigation work products; interviews; and previous research discussions. Though their report did not focus on comparing investigation methods, Henderson et al in their study of investigation drivers, methods and outcomes offered criteria for good investigations derived from surveys. The Center for Chemical Process Safety has published a comparison of 18 investigation "techniques" with eighteen attributes noted for each. The attributes used are based on "basic concepts, degree of recognition, and areas of application."

This prior work did not compare the methodologies from the perspective of their effects on investigators' specific tasks during investigations. An obvious and probably the most persuasive way to make such a comparison would be to conduct simultaneous investigations of the same accident using two or more different methodologies, and compare the investigation conduct and outputs. The project would have to be designed carefully to minimize interference between the two investigations. Before expending resources required for such a project, it seemed reasonable to try to explore a less resource-intensive approach for the comparative evaluations, to see if it might disclose differences.

The approach: The approach devised was to use data from an accident report developed with one methodology as inputs to a "desktop simulation" of an investigation with another methodology. Details about the methodology used or how they influenced the investigations tasks that produced a report are not usually reported, except for special tasks like tests or simulations, for example. However, it seems reasonable to assume that what is reported reflects the influence of the methodology used on the investigation and report

Case Selection: Because of its widespread use in the nuclear, chemical and medical fields, the methodology chosen for the data source is the Root Cause Analysis (RCA) methodology, represented by a report prepared with a variant of that methodology. The methodology chosen for the desktop simulation, the Multilinear Events Sequencing–based (MES) investigation methodology. Both were analyzed in prior studies

The case selected for this examination is described in a comprehensive accident report by the Chemical Safety and Hazards Investigation Board. [6] It is the policy of the CSB to always do a root cause analysis. An accident in a plastics manufacturing plant fatally injured three workers. The report of the investigation contains a very extensive description of that accident process, the root and contributing causes found, and recommendations to prevent similar occurrences. Although the report does not identify the investigation methodology used, the findings, the time line, the analytical logic trees and language in the report reflect the key elements of RCA, indicating the investigation methodology used was the Agency's variant of RCA.

Description of Methodologies: RCA is an experience-oriented investigation methodology evolved from the U. S. Navy's nuclear submarine program and MORT research performed for the U.S. Atomic Energy Commission. [7] MES is a self-directing rule-oriented investigation methodology, derived from observations of and experimentation with investigation processes at the NTSB and elsewhere.

RCA is a team investigation process. Investigators require extensive training in the method, because its application is heavily experience oriented. After the team is formed, the investigators begin acquiring data, using "why" questions, and use check lists, events and causal factors charts, logic trees, cause trees, and similar aids to identify and document the causal factors. After the causal factors are developed, guides offering categories of basic or root causes are available to help investigators or analysts negotiate, select and report the basic or root and contributing causes, and make recommendations. The narrative report is prepared from these data and findings. Narrative reports are usually accompanied by a chart, a timeline or logic tree to help communicate the investigation results.

RCA has many variants, but the variants have similar goals, and use many similar tools and procedures. The goals are to determine root causes of accidents or occurrences that can be used for achieving future performance improvement. Another common goal is producing recommendations about problems that "management has control to fix, and when fixed will significantly reduce or prevent the problem's recurrence."[8] The RCA investigation tools include events and causal factors charting, time lines, logic tree-based analyses like fault trees, and causal maps or guides to help investigators. Some variants use specialized tools like fishbone diagrams, Why Staircases, change analysis, barrier analysis, and energy-barrier analysis. RCA software packages are available to implement several of the variants.

MES is a self-directing system of concepts, principles, rules and procedures for any kind of investigation. [9,10] It focuses on identifying, describing, and explaining the behaviors and interactions of people and objects during accidents, and on developing changes in those behaviors that can be implemented and tracked to achieve continuous improvement in future performance. MES views the occurrence being investigated is a process, which can be flow-charted when it is adequately understood. Adapted from the structure and notations for documenting musical scores, MES uses a matrix-based structure with data documentation, organization and analysis tools and rules, plus continuing logic tests, to drive the investigation tasks. Matrix entries follow prescribed grammar and syntax rules of construction for event blocks on matrices including person, number, tense, voice and deictic position -- MES data language -- and reasoning rules to develop tested descriptions and explanations of what happened. MES then analyzes those descriptions systematically with orderly sequential problem defining, change development and ranking tasks and rules. MES provides some generalized behavioral models, guiding principles and assessment or ranking tools to convey knowledge from prior experiences to help investigators. Software implementing MES and self-directing learning tools are available.

The Simulation.

The simulation with the MES-based methodology started with the notification of the accident and creation of an MES matrix, and continued with the acquisition of more data, guided by the data already recorded as event blocks on an expanding matrix. As data were needed, the report was perused to find it and add it to the matrix. If the report did not provide needed data, gaps became visible on the matrix. These gaps were filled with inferred or hypothesized event blocks, and the report was again scanned to find supporting data. If it was not found, the matrix was marked with a "?" or e or dashed arrow or comment to highlight the gap. The evolving matrix guided the investigation effort.

The Simulation Data Source: The 97 page CSB report contains data about the facility: its history and its operation; a diagram of the process equipment involved; a description and analysis of what happened; a description of some aspects of the investigation, a discussion of relevant regulations; the three root causes and four contributing factors found; eleven recommendations; a list of seventeen literature references; a variant of an events and causal factors chart; and several logic trees dealing with specific aspects of the accident. The report does not describe the conduct of the investigation, except in a few instances where it describes tasks related to acquisition of specific data like pressure estimates, so how specific tasks were performed is not known. Thus, while differences will be observed, nothing in this paper should be construed as disparaging the CSB investigation because of those uncertainties.

Assumptions: To keep the focus on the effects of the methodology on the investigation tasks, the simulation assumes that the notification, case selection criteria, capable investigators, accessibility to data and all respective methodological supporting tools are equally available for both methods. It also assumes that all the factual data in the CSB report are true and faithfully reported. Finally, it assumes the first notification was a report within an hour of the accident that three workers had been killed by a vessel explosion in the BP-Amoco facility, and that an investigation team was dispatched from CSB headquarters based on the initial report.

The Simulated Investigation: MES-based investigations use the accident notification and case selection to initiate the investigation tasks.

The company notification informed the CSB that two employees were killed instantly when a tank end cover at its Amodel Plastics Facility blew off, and a third injured employee was pronounced dead on arrival at a local hospital shortly after the accident. The case was selected for investigation.

The first step in launching the simulated MES investigation is to create a matrix or worksheet, on which investigators document and organize data as they become available. In this simulation, information provided in the notification is used to start the documentation, as shown in Figure 1. This document is expanded as the simulation progresses, leading to a ‘flow chart” of the entire accident when it is completed.

Figure 1 shows the format of the MES matrix and its contents To permit placement on the matrix, all data used in the matrix must be transformed according to certain grammar and syntax rules into a timed actor + action format, called “Event Blocks” or EBs, the investigator’s building blocks. The unique name of the person or object is the actor, required to define the actor row on which to place the EB on the matrix. Actors are the people or objects whose behaviors produced the outcome, and whose behaviors might have to be addressed by any risk reduction proposal. Actions are required to define what the person or object did during the accident process to advance it and to define the temporal or spatial sequencing of those actions along the actor rows. Thus the matrix disciplines investigators and anyone else involved with the investigation to focus on gathering behaviors or actions –Event Blocks. RCA looks for events and conditions.

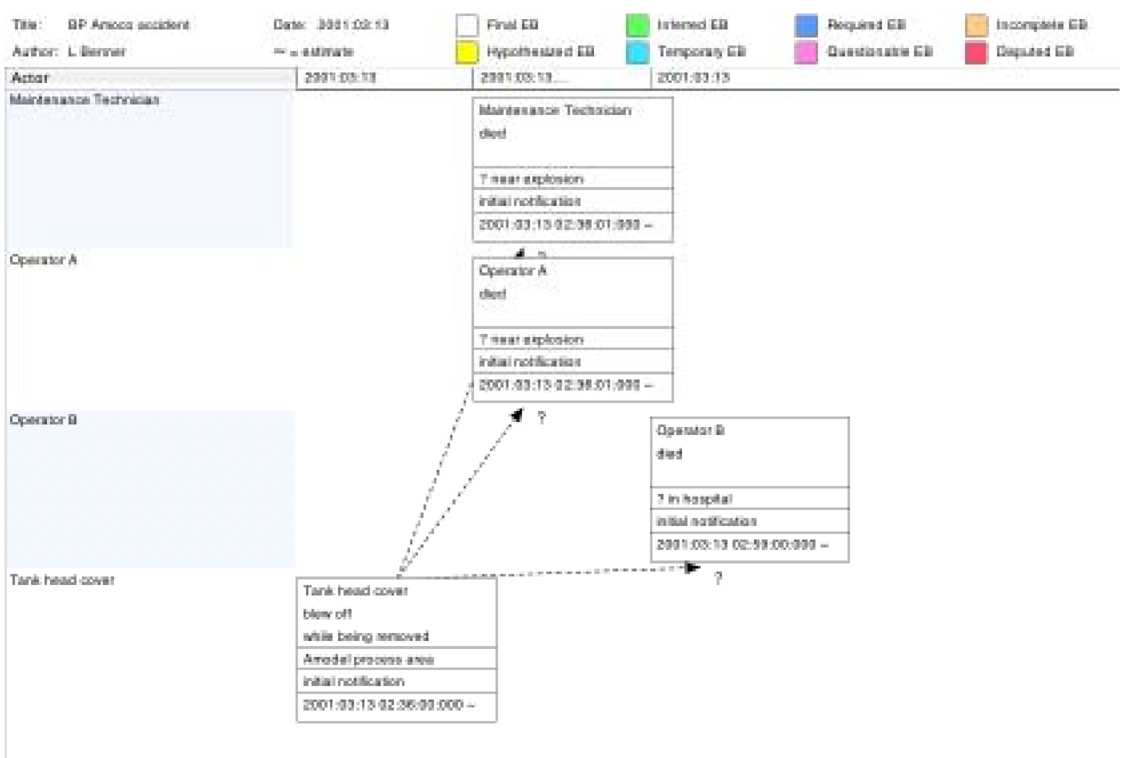

Figure 1 - Initiation of MES Matrix

The EBs also include other data used by investigators during the investigation. Each contains, in addition to the actor and action, additional attributes of the action, including the location where the action occurred, the source(s) of data from which the action was defined, the time the action began, and the time it ended. Investigators may also add reminders or notes about possible further investigation tasks or encoded colors for highlighting different kinds of Event Blocks like incomplete EBs, disputed EBs, inferred EBs, etc. RCA has not comparable requirements.

The grammar and syntax rules help overcome five common investigation problems observable during investigations and in reports:

1. Using more than one name for a person or object in the report which confuses users as they try to follow the interactions during the accident. (CSB report. page 23 uses the terms "prepolymer" and "reactor effluent" for apparently the same material.)
2. Using plural names like "the crew" or they or pronouns, which prevents the mental visualization of the accident, raising questions about the investigation. (CSB report uses many plural ambiguous terms like operators, workers, Supervision, etc.)
3. Masking incomplete or inadequate investigations by reporting actions in the passive voice, which obscures what happened, and the specific actors and behaviors that need to be changed to reduce future risk. (CSB report page 27 contains a dozen examples.)
4. Introducing assumptions, opinions or generalities unsupported by evidence acquired during the investigation into the accident description. (CSB report had none.)
5. Overlooking or not reporting behaviors that influenced the course of the accident and outcomes. (CSB report omissions are described below.)

MES requires a source for every EB. This means investigators must develop a description of what happened from observed accident data, and report when experience or other sources are used to create EBs. This source requirement also provides a tool for inventorying, retrieving and managing source materials accumulated during the investigation. RCA does not require and the CSB report does not indicate the source of all events described, so there is no way to confirm their validity, particularly in the sections describing operations just before the explosion.

The EB "begin time" requires investigators to document the timing of behaviors during the accident process when it is know, or to estimating those times to assist in the ordering of the EBs in the matrix. RCA leaves time documentation to the investigator's discretion.

The EB placement procedure on the matrix provides investigators a form of "progressive analysis" by applying four kinds of logical reasoning to the data as are added: a) sequential reasoning, for ordering EBs, b) cause-effect reasoning for establishing causal coupling, c) deductive reasoning for deriving or inferring EBs from data or bridging gaps in the event flows, and d) necessary and sufficient reasoning for determining the completeness of a description and explanation of the accident. The arrows on the matrix are a way to quickly show tentative couplings among EBs as properly sequenced new EBs are added to the matrix. RCA has no formalized linking or testing rules.

The RCA events and causal factors charting, one of the principal RCA tools, offers investigators a somewhat similar though substantially less rigorous progressive analysis capability. It uses conditions as well as events selected at the discretion of investigators, accepts ambiguous entries, often lacks timing relationships and grammar or syntax rules, and requires fewer logical validation tests, thus requiring more subjective decisions of investigators.

<u>Building the matrix:</u> Continuing the simulation, the MES matrix helps define what to look for next. On arrival at the scene, investigators typically view the scene, and try to find witnesses who can report their observations about the occurrence. In this case, the scene offered additional EBs.

These EB were taken from the report, which is assumed to have resulted from what investigators reported about the objects involved and the damage to the surroundings. For example by viewing the debris, investigators would observe that the polymer catch tank (PCT) end cover had blown off the tank; 22 (50%) of the bolts holding the cover in place, from about 7:30-1:30 on the flange, had broken; the cover struck a canopy sheltering the catch tank and landed 14 feet from the PCT; the contents of the PCT including the metal frame were expelled from the tank; and apparently, based on the position of the victims after the accident, struck the victims. It was not clear from the report whether the cover had also struck any of the victims. (The report contained an internal ambiguity on this point on pages 10 and 30.)

Adding these data to the initial worksheet, using the information from the report, one can see several more effects of the MES methodology. See Figure 2.

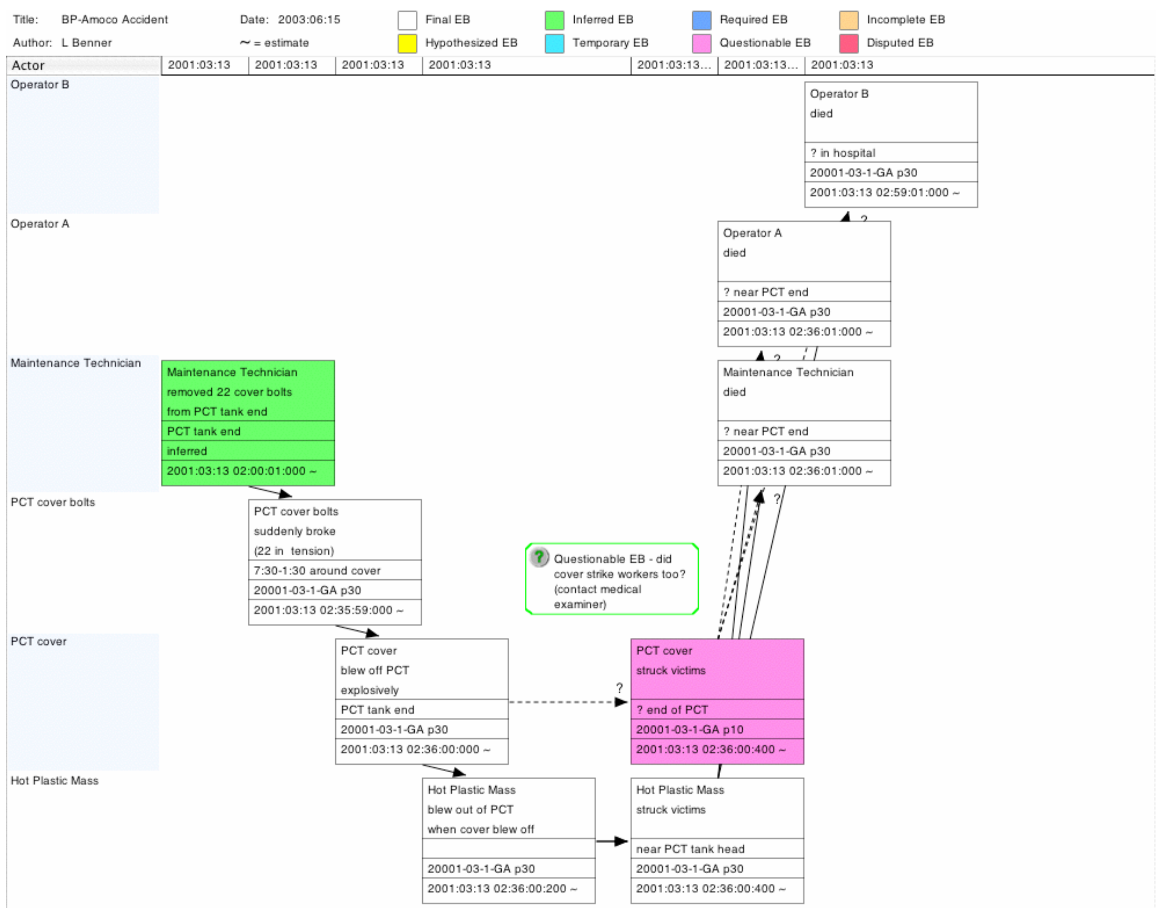

Figure 2 - Adding Data To An MES Matrix

This shows MES features affecting what investigators do and how they do it during investigations. On arrival at the site where the victims were killed, and after talking to the supervisor, investigators found additional EBs, and added them to the matrix. Two of the new EBs are color coded: the first (green) indicates to all working on the investigation that the EB is logically inferred by the investigators, and the second (cyan) indicates that that there is some question about the EB which should be resolved before the investigation is closed. The arrows were added between EBs that have a logical cause-effect or “this had to happen for that to happen” relationship during this accident.

The inferred EB illustrates how EBs evolve during the investigation. The investigator’s observation that 22 bolts holding the end cover had broken indicates that the maintenance technician had removed the other 22 bolts before the cover blew off, and may have been working on the 23rd bolt when the cover blew off. The broken bolts, together with the distance the cover flew and its trajectory after it broke away from the PCT, enable investigators to infer that a substantial internal pressure inside the PCT drove the cover of the PCT to where it went. While this seems intuitive, the EBs provide *anchors* for this reasoning process. Thus the matrix helps investigators pinpoint what to look for next, and every investigator involved in the investigation can access that knowledge at any time. Good investigators do this intuitively but informally; the matrix helps investigators capture, document and use their observations.

The report is silent on where the victims were found and the results of autopsies if they were performed. The report says they were struck by the hot plastic mass that blew out of the PCT after the cover blew off. Therefore investigators show this cause-effect relationship with a solid arrow. Because of an inconsistency in the report, there is a question about whether the end cover struck any or all of the victims, so the investigator shows a dashed arrow to indicate another open investigation data item to resolve. Dashed lines, question marks and comments show everyone all the uncertainties or problems with the accident description.

Investigators add links between EBs that are logically coupled. The links result from investigators’ spatial and temporal sequential reasoning and cause-effect reasoning. MES also requires necessary and sufficient (N/S) reasoning as the EBs are added, to determine the completeness of the links to an EB. For example, applying N/S reasoning to one of the EBs, “Hot Plastic Mass struck victims,” we find that more EBs are needed before that EB can be replicated.

MES rules require investigators to reason their way through the N/S completeness testing procedure, to help them identify all the predecessor behaviors required to produce the EB. The decision steps are supported by specific questions the investigator must answer. [11] When the EBs on a Matrix form a linked path from beginning to end, the description and explanation are complete. If gaps remain, they must be explained. Unlinked EBs are analyzed to determine if they are relevant; if the are not, they may be removed.

For the hot plastic mass to strike the victims, the victims had to position themselves in a place where the mass would strike them when it blew out of the PCT, and it had to happen so quickly that time for them to escape its path was not available. This leads investigators to pursue the reasons why the victims did that, which leads to further questions about procedures, tools and how the tools and procedures came into being. Answers are added as new EBs. These questions are continued until the investigator is satisfied that all the preceding EBs needed to reliably reproduce the trailing event each time they occur are identified and added to the matrix. For example in this case, the victims also had to remove some bolts in a certain way for the cover to blow off and let the plastic mass blow out of the PCT. The observed dispersion of the hot polymer mass indicates that the mass was expelled from the tank under considerable pressure, even though the tank was thought to be empty. Upon realizing this, investigators would add a temporary EB about something pressurizing the interior of the PCT. Pursuing this kind of reasoning can lead investigators to procedures, training, design, policies and other actions that were necessary for an EB to occur. These events would be added to the matrix, as shown in Figure 3.

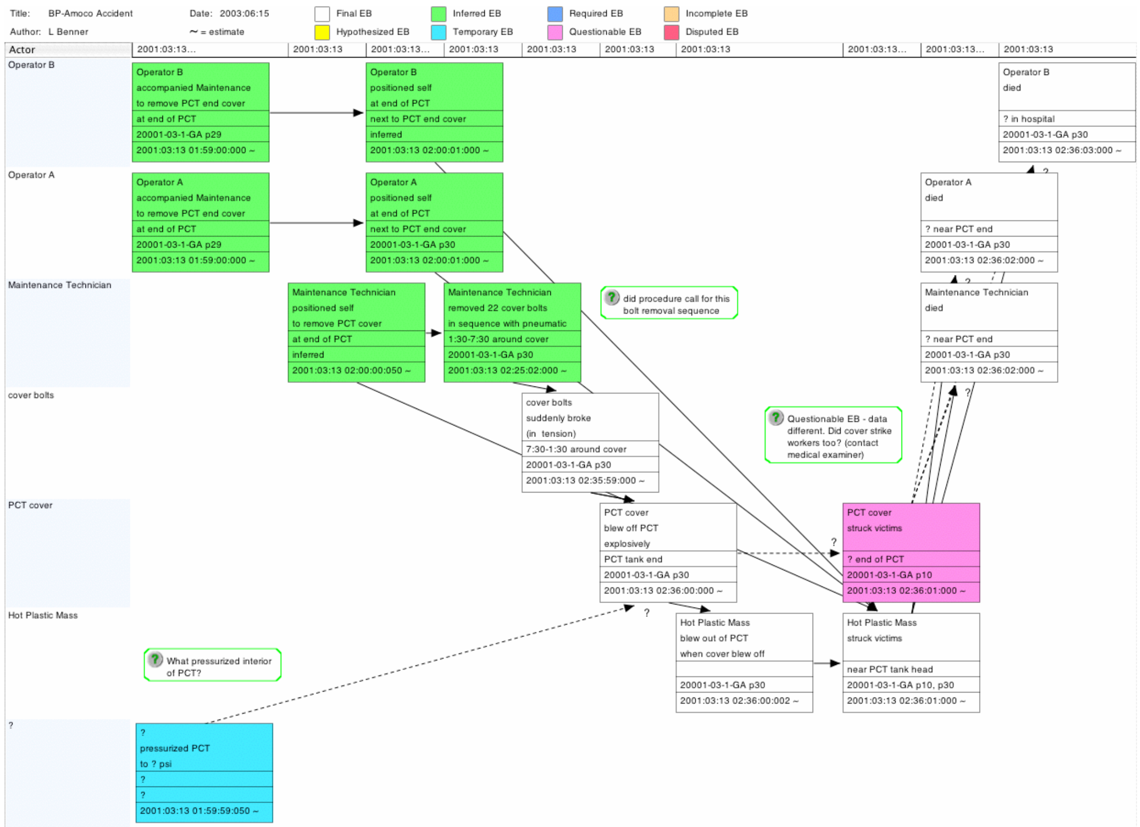

Figure 3 - MES Matrix Showing Additional Actions

The CSB report's "Timeline" describes the injury events with the first three blocks in Figure 4.

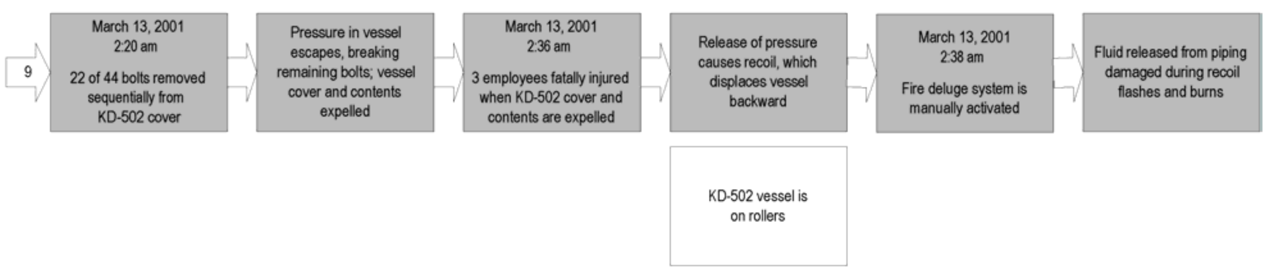

Figure 4 - CSB Timeline Of Worker Injury (page 92

RCA logic trees reflect similar kinds of reasoning about events, but the trees lack the grammar, syntax and N/S logic testing and the disciplined thinking they demand. In the absence of RCA rules for when to end logic trees, inquiry into procedures and their development depends on the investigator's judgment.

Interestingly, although the CSB report describes another accident it had investigated where 6 victims were killed when a tank cover was opened, the published graphics do not show these points. This affects the recommendations. Investigators using MES would explicitly describe both aspects in the matrix. The differences are attributable to the tasks required of investigators by the methodologies. The consequences can be observed in the differences in the outputs.

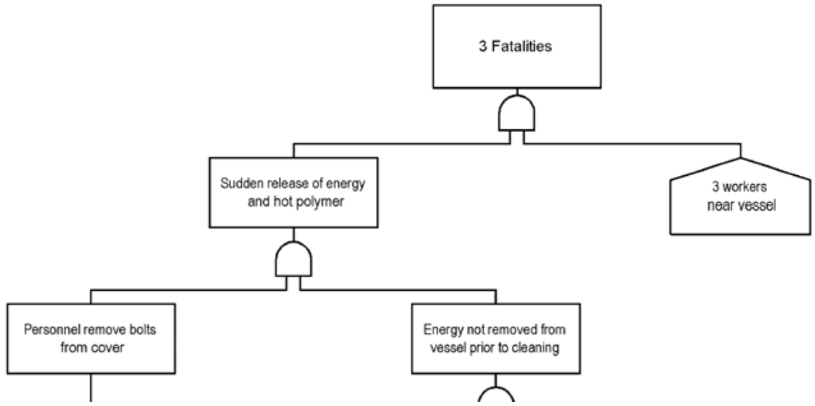

Figure 5 - Logic Tree of Worker Injury (page 93

Investigation depth: In this simulation, the part of the MES matrix developed from HAZOP data in the report demonstrates more differences. Figures 6A.1 and 6A.2 show the CSB results, and Figure 6B shows how the MES would require further investigation effort. The CSB report addresses the hazard analyses that were performed to develop safety controls for the process. The report's time line shows the problem as Less Than Adequate PHA (Process Hazard Analysis).

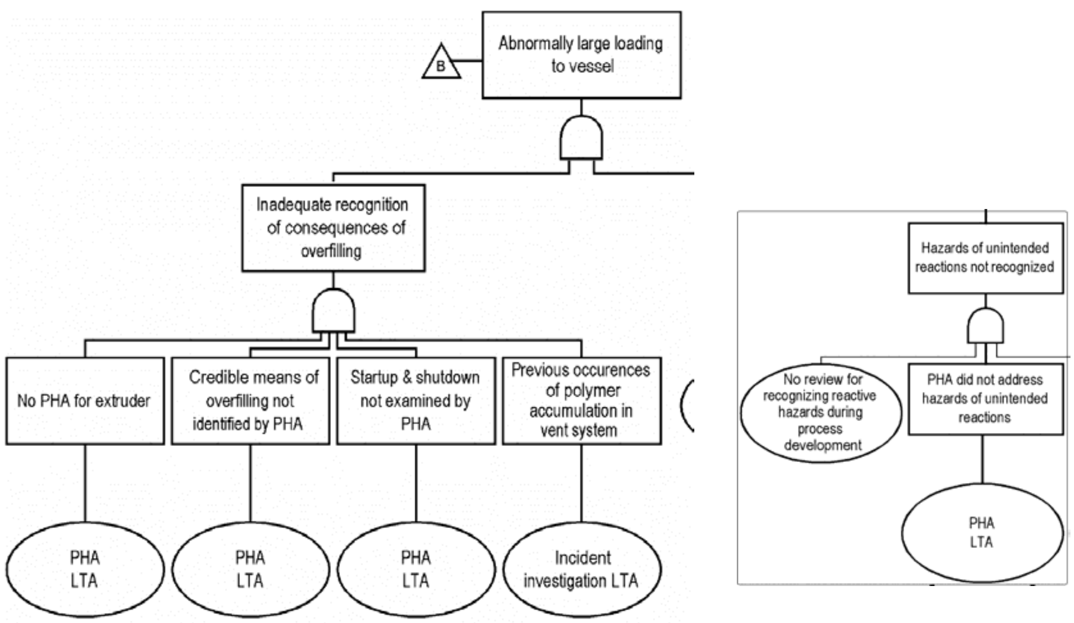

Figure 6A.1 - CSB Logic Diagrams of PHA Roles, (page 95-96)

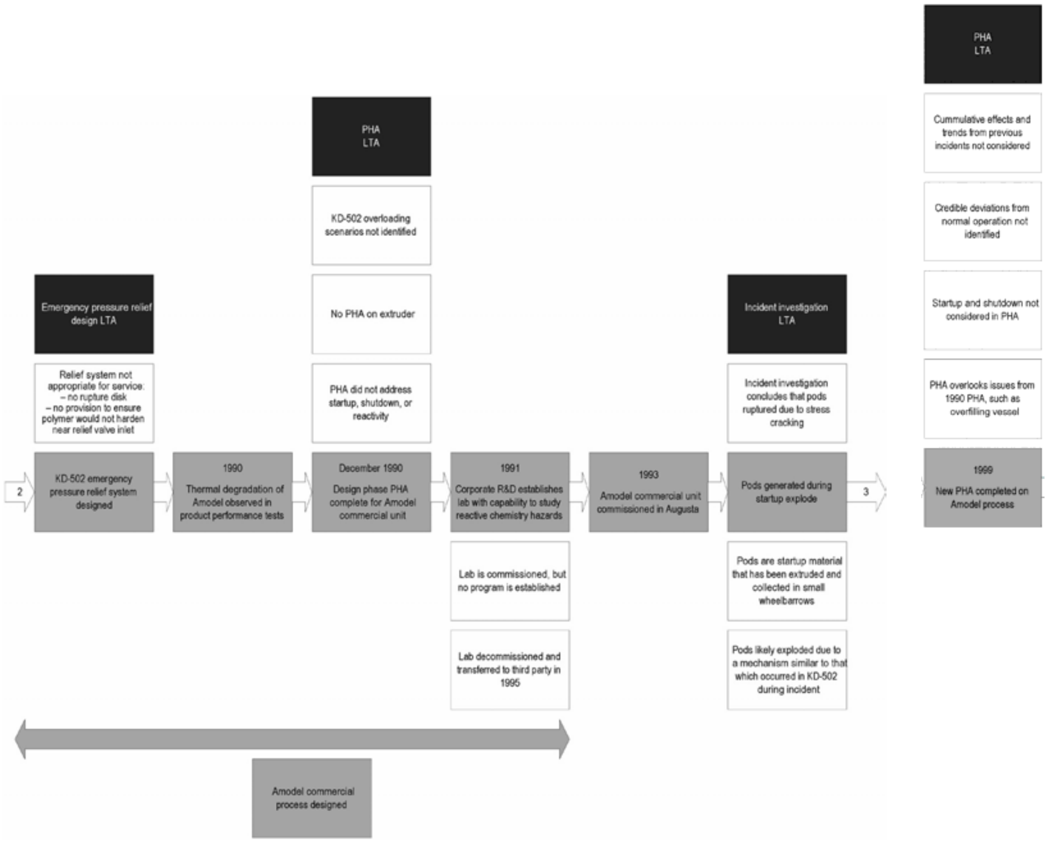

Figure 6A.2 - CSB Timeline of HAZOP Role (page 86)

The report also contains a logic diagram for the abnormally large loading of the vessel, showing the Preliminary Hazard Analysis (PHA) as an unanalyzed “basic event.”

Upon discovering that a HAZOP analysis was used for analyses of process hazards, MES investigators would try to ascertain whether the analysis method or its implementation resulted in the overlooking of the hazards or unsuccessful hazard control in this operation. HAZOP is a widely used analysis method in the industry and the difference would be important. Investigators using MES would display what happened somewhat differently. Figure 6B, abbreviated for this paper, shows the role of HAZOP analyses of the process, and shows how the EB array leads to several investigation tasks to clarify that role. Testing the EBs with necessary and sufficient reasoning leads investigators to the assumed, temporary and inferred EBs shown here, and some of them would, in turn, lead investigators to still others not yet shown. The reasoning leading to further investigation tasks is documented by the temporarily assumed EBs (blue) and the inferred EBs (green) and the questionable EB (cyan). Each indicates unfinished investigation tasks. This process could lead to management, technical or regulatory links, depending on what investigators find as they work their way upstream of the EBs shown in Figure 6B.

Incidents between the 1990 and 1999 HAZOP analyses which were not reflected by the 1999 analysis raise further questions about the analysis method and its implementation in the safety and management system; this would require further investigation to ascertain what happened during the analyses and tracking functions, and why it happened.

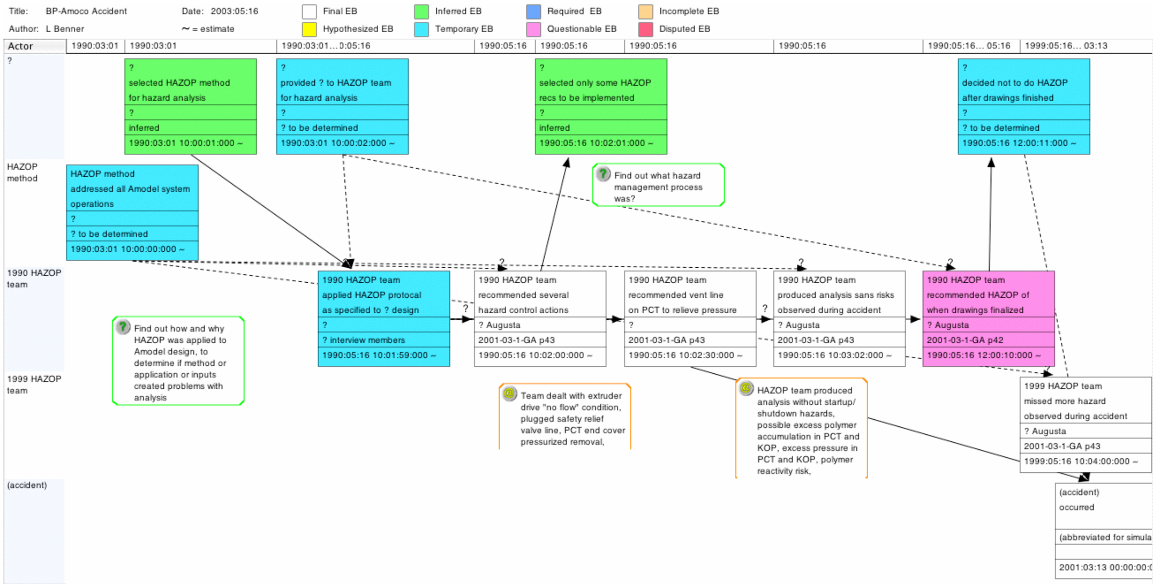

Figure 6B - MES Matrix re HAZOP Role

This significant aspect of this accident was addressed generically by the CSB report, to its credit, but it the report is unclear why the problem occurred and whether the recommendation that followed is properly directed or will achieve needed behavioral changes to reduce future risks. Further, since the desired actions are ambiguously defined, the ability to verify their successful implementation will depend on the occurrence of future incidents, rather than observations of specified behaviors during ongoing operations.

The simulated investigation continues in this manner until the origins of the accident are identified, documented and coupled, to provide as complete a description and explanation of the accident as is possible from report. As the MES investigation proceeded, it raised numerous questions, which are recorded as comments on the Matrix for disposition.

Recommendation development task: The RCA approach to defining problems is to define root causes and causal factors, which are any problem with the incident that if corrected could have prevent the incident from occurring. In RCA, the root causes are considered to be the problems demonstrated by the incident, and recommendations for remedial actions address those causes or cause factors, as was done in the CSB report. RCA provides various kinds of guidance for development of recommendations, ranging from check lists and templates to computer software.

In the BP-Amoco accident, the CSB selected three root causes: the developer's inadequate review of the conceptual process design to identify chemical hazards, the facility's lack of an adequate review process for correcting design deficiencies, and the site's inadequate system for investigating incidents' and near miss incidents' causes or related hazards. It selected four contributing causes: inadequate and incomplete hazard analyses of the process, inadequate description of the process in design documents, equipment operating procedures that did not specify what actions to take when safety precautions could not be met, and not subjecting revisions to operating procedures to management of change reviews to evaluate safety effectiveness. These causes were abstracted from the description of what happened, starting with the original development of the process until the last fire was extinguished.

The MES methodology does not use causes. Instead, it focuses on specific behaviors and interactions that need to be changed to improve future production process performance. MES strategy for identifying problems or needs is to try to identify interactions that should not occur or should occur differently to change the process flow. Investigators examine each of the behaviors or interactions which advanced the accident process and for each, define any problem it suggests. Each EB and each linked pair or set of EBs is reviewed as a potential problem, and a potential candidate for intervention in the accident process or production process. Each EB pair offers a candidate behavior to look for in future activities, which can then be monitored to ascertain whether the objectionable behaviors or interactions recur after changes are implemented. The HAZOP examples show how that would lead to different recommendations.

Discussion of results

Examples of differences observed already demonstrate that methodologies affect investigations. Are these differences important? Clearly they are, because they lead to different insights, work products, safety issues and recommendations. Their full extent is being determined. When the project is completed, a summary of the all the differences found will be prepared.

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Biography

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