"Application of Critical Thinking Concepts to Determining the Most Likely Scenario "

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Abstract : Chemical process incidents are typically accompanied by a complex chain of events involving multiple breakdowns of safeguards in "tightly coupled" systems. When identifying and determining the most likely scenario(s), there are several critical thinking skills essential for success of the investigation. Critical thinking techniques for developing, proving, disproving and evaluating potential hypothesis are examined. Common avoidable mistakes in scenario determination are identified using typical process incidents to demonstrate a more effective approach. This paper includes concepts that should be incorporated in the skill set for the investigation team.

1. INTRODUCTION

This paper reviews critical thinking skills applicable to incident investigation. Chemical process incidents are typically the end result of a complex chain of events involving multiple breakdowns of safeguards in "tightly coupled" systems.[1] Consequences of chemical process incidents can catastrophic. Much of the potential evidence is often destroyed by the event. Sometimes an investigation team may begin with a charred crater. Key witnesses are sometimes fatalities of the event. It is common practice for major process safety events in the United States to be accompanied by litigation and regulatory agency fines. It is normal for the investigation team to be confronted with conflicting information from witnesses. Part of this confusion is due to the significant emotional and traumatic impact on those who experienced the event. For these reasons, investigation of chemical process incidents benefits from effective application of critical thinking skills.

This paper examines criteria for validating potential cause scenario hypothesis, a discussion of basic principles of *critical thinking*, application of *Lateral Thinking* concepts, and guidance for avoiding a premature decision when selecting the official cause scenario. The term *critical thinking* has multiple definitions, due to the wide variety of contexts in which it is applied. One simple definition is that critical thinking is "thinking about your thinking." A more specific definition is, " *the art of thinking about your thinking while you are thinking, in order to make your thinking better* (thereby making your thinking more clear, more accurate, or more defensible).[2]

Critical thinking uses concepts of logic and reasoning to problem solving to produce more accurate and defendable conclusions. Critical thinking can guide the team in identifying what additional information may be needed to help determine validity of a suspected cause or condition related to the incident. Applied to incident investigation, critical thinking helps the investigation team to:

- identify potential causes,
- evaluate evidence in support (or refute) of a proposed cause scenario hypothesis, and
- select the most appropriate cause scenario.

The concept of critical thinking is accompanied by several additional terms: *deductive, inductive,* and *lateral thinking*. The *deductive* approach reasons from the general to the specific. Deductive thinking often looks backward in time to examine preceding events necessary to product a specified end result. In deductive incident investigation, a given failure is specified, then an attempt is made to determine what credible causes could have produced this result. The most common deductive investigation method is FAULT TREE ANALYSIS.

A second reasoning approach is the *inductive* approach, where a given fault (or failure) is speculated, then the investigation team analyzes probable outcomes which result from this specific failure. The *inductive* approach generally looks forward in time, i.e. "what would happen if ..?" A common application of inductive thinking is the HAZARD AND OPERABILITY STUDY (HAZOP), where a particular failure deviation is speculated and the study team then examines the effect on the behavior of the system (consequences). Both deductive and inductive thinking skills are used in investigation.[3]

A third thinking concept useful in investigation is *lateral thinking*. This type of thinking is popularly characterized as, "thinking out-of-the-box". When applying lateral thinking, investigators search for alternate solutions that fit a given set of conditions. One example of lateral thinking can be illustrated by this puzzle; see how quick you can identify an explanation of this event using lateral thinking.

> *A helicopter was hovering 200 ft. above the sea, when the pilot decided to turn off the engine. The rotor stopped, yet the helicopter did not crash and no one was injured. Why?*

2. CRITICAL THINKING VALIDATION OF CAUSE SCENARIOS

A primary challenge to every process incident investigation is to accurately and quickly determine the cause and event scenario. Validating a speculated scenario is fundamental to investigation success. In a purely scientific setting, when attempting to prove a theory or hypothesis, a set of six validity tests has been developed.[4] In a purely academic research environment, these tests are applied and then subjected to peer review. In practical industrial accident investigation, these same validation principles can be used to ensure a quality investigation.

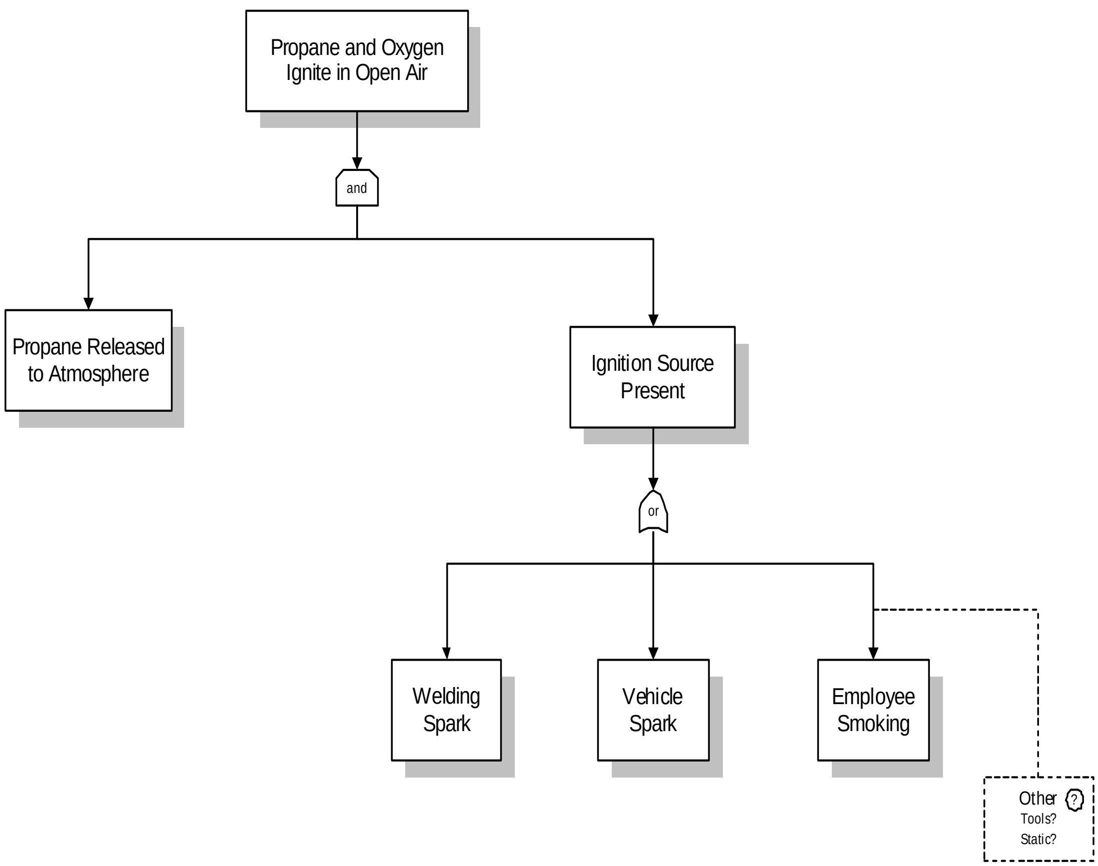
VALIDITY TEST FOR CAUSE SCENARIO SELECTION
☑ Is the scenario **logical** ? ☑ Is it **comprehensive** in addressing **all** known evidence ? ☑ Are the causes **sufficient** to create the result ? ☑ Can it be tested to prove it to be true or false ? (**falsifiability**) ☑ Can it be **replicated** ? ☑ Does it have **honesty** and integrity ?

Logic – The first validity test is to confirm the scenario and associated facts agree with accepted logic principles. For the purposes of this paper and for the purposes of validity testing incident scenarios, the term logic is defined as " *the scientific study of the principles of reasoning, especially of the method and validity of deductive reasoning.*[5] This logic validation test is not usually a problem for chemical process investigation, since most investigation team members are technical personnel who are trained and experienced in applying a logical thinking to problem solving.

Any argument offered as evidence to support or disprove a suspected incident cause hypothesis, must follow accepted rules of logic. Two excellent examples of the application of this logic test are the Fact-hypothesis Matrix,[3] and the use of Truth Tables when testing the output of binary electronic circuits or when diagnosing/troubleshooting instrumentation systems. For investigation of complex events, a deductive logic diagram such as a FAULT TREE diagram is often developed in order to examine the relationship between known facts and conditions. The FAULT TREE logic diagram uses rigorous and formal rubrics such as logic gates ("*AND* " gates, "OR" gates, and others). The Management Oversight and Risk Tree (MORT) investigation methodology is based on a generic fault tree containing some 1600 gates. The investigation team then systematically examines each potential branch of the MORT Tree for applicability. A properly executed logic diagram can quickly highlight evidence which is inconsistent or which contradicts aspects of a proposed incident cause scenario.

A simple example of an incident investigation logic diagram is given in Figure 1. This logic diagram illustrates an investigation of an employee slip-trip-fall accident. The team applies the

Investigative FAULT TREE Fig.1



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logic diagram in an iterative manner to identify what conditions and actions were present or were needed for the accident to occur. The initial logic diagram may contain several speculated "OR" gates, where insufficient information is available to determine if the branch was applicable. The logic diagram will highlight missing pieces of information and thereby guide the team to gather additional focused information. Once there is sufficient evidence to refute a particular cause or condition branch, further development of this particular branch is terminated and the determination is documented. Near the final stages of the investigation the logic diagram used in a quality assurance mode to verify that the known facts meet logic principles and that each branch is in agreement with all other branches of the logic diagram.

The investigation team may encounter circumstances where a branch of a logic tree cannot be resolved completely due to insufficient evidence. There may be several credibly possible failure modes that could have occurred (OR gates) and the team may not be able to determine exactly which failure or condition occurred in this incident. A common example would be the case where there is insufficient evidence to determine which of two ignition sources actually ignited a fire. In these cases, it is appropriate to take preventive action for each credibly possible ignition source.

Comprehensiveness
The second validity test confirms that all known information has been included in the evaluation. The team does not have the luxury of being selective about which facts it accepts, even if a particular fact does not support the preferred hypothesis. Most of us have strong and automatic filter mechanisms built into our cognitive processes. There is a natural tendency to welcome information that supports our preferred (or perceived) hypothesis. We also have a corresponding tendency to "reject" information that does not support or fit into our desired hypothesis (our desired cause scenario). At the conclusion of the investigation, if there is any evidence available that contradicts the cause scenario, reasons for refuting this contradictory information should be adequately documented, well understood, and accepted by the investigation team.[6]

In purely scientific research activity, this comprehensiveness validity test is easier to apply. In the practical world of industrial incident investigation, there are varying degrees of credibility regarding the accuracy of information. Not all information available to the investigation team has the same degree of truthfulness and accuracy. It is difficult in some cases to determine which information is the more accurate. The team will often be initially faced with apparently contradictory information. In most, but not all cases, these apparent contradictions can be resolved by gathering additional clarifying information. For those unresolved conflicts in information, the team must document these inconsistencies and provide explanations wherever possible.

Inconsistent or conflicting information is especially common in information gathered from witness interviews. People's memory is imperfect. We recall what we believed (perceived) to have happen, not necessarily what actually happened. Our minds will automatically fill-in missing details and adjust our perception without us realizing it. Whenever two witness discuss the incident with each other, their understanding of the event will change, and therefore their perceived memory of the event will be invariably altered.[7]

If the team cannot reach consensus on evidence or findings, one approach is to include a section in the final report that presents an alternate possible version of the cause scenario. Justification reasons in support or rejection of each alternate explanation should be included in the documentation.

Sufficiency –
The third validity test is *sufficiency*. Evidence offered in support of a cause scenario must be adequate (sufficient) to establish proof. If a scenario requires three components to be present, then the investigation team must establish the credible presence of all three components. One example

of application of this validity test occurred recently in a steam manufacturing unit that used hydrogen as fuel. A steam generation vessel failed catastrophically and instantaneously. The investigation team was unsure if the event was caused by an internal hydrogen explosion or if the event was the result of a very rapid phase change of water into steam (sometimes called a "steam explosion). Initial evidence was inconclusive. After additional investigation and evidence gathering, the team was able to determine there was no credible possibility for sufficient hydrogen to accumulate in the vessel, and therefore the fuel component for the explosion hypothesis could not be satisfied. The test of *sufficiency* was not met for the case of a hydrogen explosion event. The team concluded that there was no ignition or combustion and that the incident was the result of a rapid and violent flash expansion of liquid water into steam.

<u>Falsifiability</u> -
The fourth validity test, *falsifiability*, has a curious and potentially confusing title. The test of *falsifiability* requires that it must be possible to design and conduct a test that has the ability to prove a suspected scenario to be false. It must be theoretically possible to find evidence that has the potential to refute the hypothesis. The investigation team then would search for this refuting evidence during the investigation. Consider the following example, where chlorine gas was released when a control system malfunctioned:

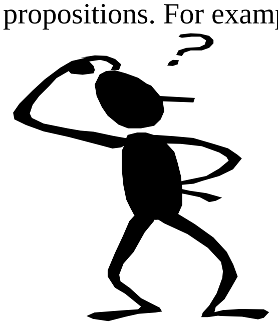
> Suppose the incident investigation team speculated one possible cause event was freezing of a water-glycol mixture in a section of instrument air process piping which therefore interrupted instrument air supply to a control valve. The team knew it was not unusual for this mixture to be present in this section of piping. The freeze point of this mixture had never been determined and the team was unsure that this freezing was a credibly possible cause scenario. The team speculated the process temperature reached –2 ° F. The team suspected the glycol-water mixture accumulated in the lower portion of a piping loop, froze, and created a flow obstruction. This obstruction resulted in an upset to a primary control valve, which then malfunctioned and subsequently caused a release of chlorine gas to the atmosphere.
>
> In order for the team's hypothesis to meet the test of *falsifiability*, it must be possible to devise a test to determine behavior of this water-glycol mixture at temperatures at -2 °F (at operating pressure). As part of the investigation, the team was able to determine by actual controlled testing, this particular mixture <u>would</u> freeze at temperatures at or below -2 °F (at atmospheric pressure). In this example, there was the ability to gather evidence which had the potential to disprove the speculated hypothesis. If the mixture did not freeze at –2 F, then the team's suspected cause hypothesis would be proven to be false. In this particular case, the proposed scenario did satisfy the test of *falsifiability*.

<u>Replicability</u> –
The validity test of *replicability* requires any evidence based on experimental results must be able to be duplicated by others using the same conditions. One well known example of non-Replicability is the Cold Fusion controversy . In 1989 two scientist from the University of Utah believed they had discovered a method for cold fusion.[8] It became quickly evident that other scientist could not replicate the results and the hypothesis was ultimately rejected. An industrial investigation example of the replicability test, would be the case where some contaminant in the reactor feed streams initiated an adverse chemical reaction. The investigation would attempt to replicate (on a smaller scale) the inadvertent reaction to determine if this was a valid cause scenario. For chemical reaction incident investigations, exothermic reactions must be able to be replicated, albeit on a smaller scale.

<u>Honesty</u> –
The final validity test is *honesty*. On the surface this test seems to be an obvious requirement. However in the handling and presentation of evidence, there are opportunities for misleading or incomplete representation of the facts. The investigation team must exercise a high degree of honesty and integrity, even when pressure is applied by special interest, and even in cases where the findings do not favor the organization’s reputation. Omission of pertinent information can have a significant effect on litigation findings. Documentation of evidence and findings will often come under the control of the organization's legal department, however this control does not eliminate the requirement for the investigation team to honestly address all available evidence. Evidence must be honestly and truthfully evaluated with as much objectivity as is possible. There is an obligation to draw rational conclusions after considering all the available information. If the team cannot satisfy this *honesty* test, then investigation team findings are, by nature, invalid. There is an obligation to document any unresolved inconsistencies.

3. CRITICAL THINKING APPLIED TO INCIDENT INVESTIGATION

Effective thinking is essential for accurate determination of the scenario, causes and cause relationships in every process safety incident investigation. Investigators must apply logic and reason effectively. Reason is the ability to discern the logical relationships between concepts and propositions. For example:



1. ***if*** the temperature in tank A was higher than in tank B,

   and

2. ***if*** the temperature in tank B was higher than in tank C,

   ***then**, by logic and reason*

3. the temperature in tank A **<u>must</u>** have been higher than in tank C

Another challenge to investigators is determining which information is actually true. Investigators will often be faced with apparently contradictory information from witnesses. Many witness statements are combinations of actual true facts and personal opinions and judgments on the part of the witness. Witness statements are a combination of first-hand (first generation) information, assumptions, conclusions, and hearsay (second generation information). We all realize that information relayed in a verbal manner is subject to distortion and inaccuracy. Two examples of verbal communication information modifications are “sharpening” and “leveling”. “Sharpening” occurs when we slightly modify a verbal message to emphasize certain information that we believe to be of more importance, priority, or significance. “Leveling” is the opposite of sharpening. In leveling, we de-emphasize or omit information that we judge to be of less importance to the person we are relaying the information to. In some cases, we are not even aware that we are modifying the information during the transfer. Absolute truth is not created by consensus of opinion. Just because a lot of people believe something, does not make the information to be a true fact. Here are several historical examples of opinions that were widely believed to be true but are not based on any verifiable truth.

Are these statements* FACTS *or “* CONSENSUS OPINION*” masquerading as facts ?

- *“ The earth is flat.”*
- *“ The sun revolves around the earth.”*
- *“ Accurate prediction of the future can be made by autopsy of a human liver. (according to the early Babylonian practice of hepatoscopy) .”*[7]

Incident investigators often encounter cases of subjective opinion masquerading as truth. When analyzing information that may or may not become pertinent evidence, it is important for the investigation team to distinguish between objective fact and subjective opinion. A current example of group opinion is the widespread belief in Astrology. It is reported that 25 % of Americans (including 55 % of teenagers) believe in Astrology despite the absence of any scientific validation.[7] Just because a large number of people have an opinion that Astrology is based on fact, does not in-itself make something a fact.

There are several categories of truth. A *necessary truth* is a statement that cannot possibly by definition be false. Examples of necessary truth are:

- 2 + 2 = 4,
- bachelors are single,
- red is one of the colors

A *necessary falsehood* is a statement that cannot by definition be true. Examples are

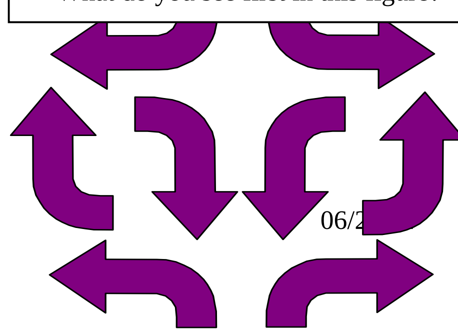
- 2 + 2 = 5,
- bachelors are married,
- red in not one of the colors

Investigators must recognize necessary truths and falsehoods. Investigators should be alert for dogmatic statements that may not be supported by actual evidence. Dogmatism is establishing conclusions on rules, conditions, protocols and prescriptions established by some authority. Just because oxygen tests are required (by management authority and implemented procedure instructions) prior to entry into a combined space, does not mean that the test was actually conducted in the instanced being investigated. Dogmatic requirements should not be mistaken for actual facts. The investigation team must verify assumptions. Any stipulations should be clearly and thoroughly identified in the investigation report.

Anther critical thinking challenge to investigators is the occasional conflict between something that may be logically possible, but is physically impossible. Although it is logically possible for a cow to jump over the moon, in the practical world there are physical limitations that prevent this statement to be physically possible. Just because something is logically possible, does not mean that it must be accepted as a true fact in the investigation.[7]

Memory inefficiency is another variable that must be managed by investigators using critical thinking. Significant differences in witness statements can be traced to our natural and normal imperfect memory mechanisms. Investigators must apply critical thinking skills when faced with apparently contradictory information from different witnesses. Our memory does not function like a tape recorder. When we "remember", we are recalling and reconstructing our perception of what we think we saw. Our perception can change over time as we loose the ability to recall details (for example, a person's name) and as we gain additional information from interaction with other people and access to other information sources.[7]

What do you see first in this figure?



Perhaps the greatest single obstacle to evidence analysis is our natural information filtering mechanisms that are part of our normal thinking processes. Our perception of reality is actually a mental construction of several components. Three primary components are: inputs from our senses, our expectations based on our prior experiences, and our pre-existing set of beliefs and convictions. When faced with incomplete or potentially contradictory information, our brains will fill in the blanks to allow us to process and "make sense" of the incoming information. The most common example of this is the optical illusion, where our brain makes a determination when faced with ambiguous input.

4 LATERAL THINKING

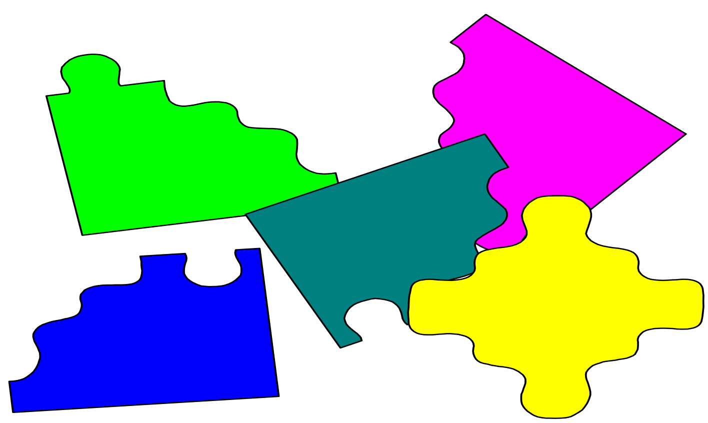
Lateral Thinking is the name give to the concept of seeking alternate (non-traditional) explanations to a given set of information or circumstances. *Lateral Thinking* allows and encourages investigators to deviate from normal conventions and expectations. Creativity is used to identify possible alternate explanations for evidence presented. *Lateral Thinking* concepts are extremely useful during early stages of an investigation or when there are apparent inconsistencies in evidence. When presented with a set of circumstances, our first response is to try to find a traditional explanation that fits the facts as we understand them to be. A *Lateral Thinking* approach to incident investigation cause scenario identification, would not reject the most likely explanation, but would also expand to include alternate less probable explanations for the same set of facts. Alternate possible scenarios remain on the table until there is clear reason for rejecting them.

In the *lateral thinking* approach, investigators are encouraged to temporarily put aside conventional norms and look for lower probability circumstances. *Lateral thinking* skills are beneficial to the investigation by ensuring all credibly possible scenarios and causes are identified and evaluated. Creative thinking (out-of-the-box) is not always welcomed by all parties. It sometimes generates extra work for the investigation team to document reasons why alternate explanations were rejected. Nevertheless, it adds to the overall quality of the investigation and makes the ultimate findings more credible and defendable. There are numerous websites devoted to *lateral thinking* currently on the internet.

The answer to the earlier helicopter puzzle becomes obvious once you are given the additional information. The helicopter was making a routine landing on the helideck of an offshore oil platform. The landing platform was 200 feet above the sea.

5. SELECTION OF CAUSE(S) & SCENARIO

Rapid and accurate identification of the cause scenario can be adversely affected by several factors.



One obstacle faced by investigators is the temptation to make a premature decision on selection of the cause scenario. The team should begin by identifying several potential scenarios and should resist the temptation to prematurely select one potential scenario above all others as “the “official and final scenario. The investigation must eventually identify and examine all credible potential cause scenarios and ultimately select one cause scenario as the most likely based on the available facts. Early establishment of “a most likely scenario” is not a mistake, as long as alternate scenarios remain under consideration until there is sufficient evidence to reject the alternate scenarios. Premature final selection of the cause scenario can create avoidable mistakes. The first problem is the resulting delay in finding the actual cause, due to the team investing time, money, and resources pursuing a false trail. A second potential problem is triggering irrational defense of an invalid scenario. Investigators are slow to abandon a preferred cause scenario, even when faced with evidence that would clearly disprove the scenario. The third potential problem is the loss of credibility generated when the team has to announce that their initial findings and conclusions were incorrect. This decreased credibility casts an extra amount of doubt on all future teams findings, which has an adverse impact, especially in instances where litigation is involved.

Determination and selection of “the cause scenario” involves rationalization. According to Psychologist Barry Singer,[7] numerous experiments have confirmed our natural behavior regarding how we develop hypothesis and conclusions. It is our normal pattern to very quickly (and automatically) form a hypothesis and then begin to seek confirming evidence. We do not inherently place emphasis on seeking evidence that might disprove our hypothesis. We tend to stick to (and vigorously defend) our original hypothesis even when faced with conflicting evidence that might disprove our desired hypothesis. Investigators therefore should make a strong and conscious proactive effort to operate with an open unbiased approach, especially during the early phases of an investigation.

One potential trap for investigators is the *self-fulfilling* prophesy. A classic example would be the rumor of an impending bank insolvency. Even though a bank itself may be solvent and financially stable, the rumor of insolvency has the ability to create a panic. The consumer reaction then results in a run on the bank, which can result generating a potentially insolvent condition. Another recent (late 1970’s) and more humorous example was the rumor of a possible nationwide toilet paper shortage. This caused a surge of buying as consumers to immediately attempt to stock-up. The buying binge then created an actual temporary shortage in the retail stores.

We very often see what we expect to see and force mental interpretations where there is no clearly established pattern. We rely on our past personal experiences and the “conventional wisdom (conventions & expectations)” that we have accumulated to draw conclusions and make judgments about what we are seeing. Once the team establishes a probable scenario, the team needs to ensure that it continues to evaluate incoming information with an objective attitude.

Another challenge to investigators is the false or hidden assumption. It is sometimes very easy to make false assumptions regarding the association between truly random events, thus generating a cause and effect correlation where there is not a direct cause and effect. One example would be the “red car phenomenon.” A popular (but erroneous) belief is that red cars are more dangerous as evidenced by higher insurance premiums. Is the color red really a cause of increased accidents? Is it more likely that people who select red colored cars are the source of the problem and not the actual color of the paint? Hidden assumptions can play havoc with an investigation, where a team makes an assumption without realizing that an assumption has been made. These hidden assumptions often show up as inconsistencies in the cause scenario. When assumptions and stipulations are made, they should be clearly identified and documented.

Misjudging likelihood/probabilities can lead to erroneous determinations by investigation teams, where the team believes a cause event to be too unlikely and therefore fails to thoroughly investigate a particular cause. Most of us are not naturally proficient at estimating likelihood or probabilities of events. We remember confirming events much more effectively than we remember events that do not confirm a perception. Despite repeated studies, there is no confirming scientific evidence that a full moon is accompanied by increased birth activity. Births that occur during a full moon are remember and noted as confirmation of our belief that a larger number of births occur during a full moon. Repeated statistical analysis studies have not shown any increase in birth rate.

Numerous examples can be identified that illustrate our inability to accurately estimate probabilities. Perhaps one of the more common examples relates to our inherent inability to accurately estimate the odds of two people having the same birthday (same month and date). If there is a group of 37 people, and we are asked to estimate the probability that two of these people share the same birthday, our initial guess might be in the range of .1. Our initial thinking might lead us to believe that the likelihood should be in the range of 1 in 10, since there are 37 people in the room and there are 365 days in the year. The actual probability based on statistics is much greater than .5.

Part of our weakness in estimating probabilities is the inconsistent reporting of accidental deaths in the popular news media. Many people have great fear of flying, yet they are safer while on a commercial flight than they are when they are in a vehicle going to or from the airport. Approximately 40,000 people are killed yearly in the US in traffic accidents . The average annual aviation death total remains less than 1000. News media coverage of aviation deaths is greater than traffic accident deaths, due to the spectacular nature of air crash events. One hundred people dying in a single aviation crash each is more newsworthy than one hundred people being killed in one hundred single vehicle traffic accidents. Our perception of likelihood is affected by the more spectacular news media response to aviation accidents.

A final challenge related to rapid and accurate determination of the cause scenario is misplaced credibility. All other things being equal, we put more credibility on the first version of story we hear. Subsequent versions that differ from the initial version are given less credibility, because we activate some of our natural mental filters.[6]

For more effective cause identification,… AVOID

- over-resistance to abandoning a preferred cause scenario when faced with contrary facts
- biased non objective screening of information that does not fit the desired scenario
- self fulfilling prophesy
- misjudging probabilities/likelihood
- false, hidden, or incorrect assumptions

6. CONCLUSIONS

Critical thinking concepts are not new issues for experienced process safety incident investigators. Some incident investigation management systems incorporate *critical thinking* skills in the written investigation procedure and in the team training activities. For improved investigation effectiveness, use *lateral thinking* in the early stages to develop possible cause scenarios. Ask if there are any other ways (non conventional, anomalies, lower probability events and conditions that could provide another way to explain the facts as you understand them. Remember to be open minded if and when additional information becomes available late in the investigation that does not support your chosen cause scenario. The following checklist may be a useful addition to your next investigation or to your root cause incident investigation system training manual.

	CHECKLIST FOR CRITICAL THINKING DURING INVESTIGATIONS
☑	Give objective review & consideration for all evidence
☑	Be aware of filtering, sharpening, and leveling when analyzing information
☑	Make a serious and objective attempt to <u>disprove</u> your favored hypothesis at several stages during the investigation
☑	Determine if you are dealing with <u>first generation information or later generation</u> information and treat second generation information with a different degree of accuracy
☑	Make conscious effort to <u>delay final selection of the cause scenario</u>, until all credible alternatives have been objectively evaluated.
☑	Apply the six validity checks before making a final decision on the cause scenario

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