Lessons Learned from Scenarios Found during PHA of Startup, Shutdown, and Online Maintenance

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Abstract

Hazards may go unrecognized or underappreciated due to a variety of influences. Ignorance of the hazard is a convenient excuse after an incident. Many incidents are touted as black swan events when they are quite predictable. This paper shows examples from many PHAs of scenarios found from startup, shutdown, and online maintenance modes of operation for which there were no or not enough IPLs. These include (1) introducing cryogenic liquids in columns or vessels before ensuring proper pressurization with gas, (2) valves being left in the wrong position despite many double checks, (3) valves opened or closed in the wrong sequence, despite checklists and significant emphasis, (4) purges being left off despite frequent checks by multiple shifts, and other similar incidents. These types of scenarios have led to many well-known and extremely costly industrial incidents around the globe and may be lurking now in plants operated by the reader, unprotected against and ready to wreak havoc.

The paper describes how these scenarios are found and how they can be prevented using a basis of human reliability and risk assessment of abnormal modes of operation (PHA of Procedures).

1 Introduction

There are several reasons that human errors are both more likely and more devastating in abnormal modes of operation. First, the close interaction between humans and the process equipment adds opportunities to introduce errors that are normally not possible during normal operation, effectively raising the chances for error by sheer increased exposure and input from the operators (especially during startup). Second, during modes of operation such as shutdown, startup, or online maintenance the level of contribution from Human Factors that drive error frequency are multiplied, making human error more likely per interaction/input. Lastly, during abnormal operation, some or all of the critical Independent Protection Layers (IPLs) are not available; or worse, were never included in design to account for certain scenarios possible in these modes.

Following several large industrial catastrophes, the US government through OSHA established regulations requiring companies to perform Process Hazard Analysis (PHAs) as part of their Process Safety Management (PSM) system. OSHA intended that PHAs cover hazards and accident scenarios during all modes of operation.

Over the past 3 decades since these regulations were established, performing PHAs has become commonplace in chemical plants, gas plants, oil refineries, and related processing plants around the world. Though the US PSM regulation requires PHA of all modes of operation, only a minority of companies actually invests time in meetings for analysis of these non-routine modes of operation (apart from normal HAZOP brainstorming: analyzing deviation of level, pressure, flow, and other parameters). Most companies consider the PHA complete and within compliance if they cover the standard 'Deviation during startup, shutdown or maintenance' as topics during the HAZOP of continuous nodes of equipment to satisfy the requirement of the PHA to include all modes of operation. Unfortunately, this type of brainstorming is not adequate to identify most of the scenarios that can occur during non-continuous modes, catching only 5-10% of the unique scenarios that can occur during these modes of operation.

Studies performed by regulators and industry analysts have shown more than 70% of major accidents occur during non-routine/abnormal mode operations (startup, shutdown, online maintenance primarily). This paper gives examples of several scenarios that would have been missed by the typical method of HAZOP of nodes plus 'Deviation during…' used by the vast majority of companies during their PHAs (about 80% of companies use this analysis, according to estimates by PII). The value of identifying and protecting for scenarios found as part of abnormal mode PHAs (accounting for costs of extra meeting time) will be shown through these examples. According to statistics from PII and other PHA data, additional savings from avoided incidents from recommendations generated in PHA of abnormal modes/Procedure often provide 5 times the risk reduction compare to the recommendations found from PHA of normal mode of operation.

Most of the observations and statements above are from the definitive paper on PHA of procedures and Chapter 9 of Guidelines for Hazard Evaluation Procedures, 3rd Edition. [1, 2].

2 Human Factors based approach used in identification

In order to understand how the example scenarios were identified, and to illustrate how most companies can improve the quality of their meetings sufficiently to see the same results, potentially saving hundreds of millions in avoided costs per scenario, the Human Factors based approach recommended by PII for brainstorming abnormal modes is described briefly below (these were described in detail in a previous paper on this topic):

To fully address human factors during PHA/HAZOP, a four-step approach is suggested [3]:

- *Step 1: Ensure education and experience of PHA/HAZOP Leaders in human factors and human error prevention. Also ensure the PHA/HAZOP Leaders are competent in PHA of procedures (which is very different than PHA of equipment nodes)*
- *Step 2: Ensure the brainstorming of scenarios includes consideration of human error and even multiple human error as causes; be specific as possible on the human error.*
- *Step 3: Have the PHA team perform a hazard review of procedure steps using a HAZOP or What-If analysis to uncover potential human errors associated with modes operations such as startup, shutdown, and online maintenance.*
- *Step 4: Supplement the PHA/HAZOP of the individual scenarios with a checklist analysis of general human factor issues, to ensure all major categories were addressed*

Using the Human Factors approach, the PHA team focuses on finding scenarios in abnormal or non-continuous modes, such as startup, shutdown, and online maintenance by considering human errors that can occur while performing steps in a procedures for these different modes of operation; i.e. when can operators make errors, how can they make errors, with what frequency, what are the consequences, and is the process protected given an error occurs?

Step-by-step HAZOP and/or What-If analysis is not new to industry, and regulators have required similar approaches for decades, adding language to specify type of analysis.

This approach outlined above is an accordance with the US OSHA PSM regulation, 29 CFR 1910.119,9 and similar requirements in US EPA's rule for risk management programs (RMP), 40 CFR 68.24,10. These specifically require that PHAs consider and address hazards of the process during all hazards regardless of the mode of operation (routine or non-routine).

- 29 CFR 1910.119(e)(1) states that the PHA, "shall identify, evaluate, and control **the hazards** involved in the process"
- 29 CFR 1910.119(e)(3)(i) states that the process hazard analysis shall address "**The hazards of the process**".
- 29 CFR 1910.119(e)(3)(vi) states that the process hazard analysis shall address human factors.
- Appendix C to the OSHA PSM standard states that both routine and non-routine

activities need to be addressed by the PHA of the covered process.

Increasingly, non-US based companies are also requiring that all modes of operation be covered in the analysis. For example, SHEMS 2.01, the standard for SABIC affiliates in the Kingdom of Saudi Arabia and world-wide lists the following, under PHA Study Scope:

- "4.8.8.1 The PHA study shall consider the following, as applicable, for all modes of operation including normal, startup, shutdown and emergency shutdown / operation... [4]"

And many other companies around the world require PHA of procedures as part of a complete PHA, including PLUS-PETROL and PAN AMERICAN ENERGY in Argentina and Peru, ECOLAB/NALCO (Worldwide), CHS Refinery (USA), GPIC (Bahrain), CHEMANOL (Saudi Arabia), ARAMCO (Saudi Arabia), etc.

However, despite new and more exact requirements by codes and standard added, regulators continue to note lack of analysis of the risk of non-routine operations and lack of risk review of changes to procedure, as provided in findings from incident reports of well-known disasters. Below are just a small example of such findings.

> ***From the Wall Street Journal [5] referencing the presidential commission investigating the Deepwater Horizon accident of April 2010:*** *BP had rules in place governing procedural changes, but its workers didn't consistently follow them, according to BP's September [2010] internal report on the disaster and the report released earlier this month [January 2011] by the presidential commission on the accident. "Such decisions appear to have been made by the BP Macondo team in ad hoc fashion without any formal risk analysis or internal expert review," the commission's report said. "This appears to have been a key causal factor of the blowout."*
>
> ***From CSB Report on August 2008 Bayer CropScience Explosion [6]:****"The accident occurred during the startup of the methomyl unit, following a lengthy period of maintenance … CSB investigators also found the company failed to perform a thorough Process Hazard Analysis, or PHA, as required by regulation…In particular, for operational tasks that depend heavily on task performance and operator decisions, the team should analyze the procedures step-by-step to identify potential incident scenarios and their consequences, and to determine if the protections in place are sufficient."*

More regulatory pressure is sure to follow, since major accidents continue to occur during non-routine modes of operation.

How does someone responsible for coordinating or performing hazard evaluations (including PHAs) uncover potentially important accident scenarios during all modes of operation without consuming too many resources? To correctly answer this question, we must (1) understand the root causes of human error and (2) develop a

strategy for systematically finding the scenarios that are caused by human error, during all modes of operation. The strategy must be thorough yet provide for a practical allocation of resources. This paper provides a strategy that uses widely accepted hazard evaluation techniques (such as those referenced by OSHA and EPA for PHAs, which include what-if analysis and hazard and operability [HAZOP] analysis). This strategy has proven effective for hundreds of facilities over the past two decades since it was first published.[1] In addition to identifying accident scenarios during non-routine modes; this approach helps to more fully address human factors, which is a specific requirement of OSHA's PSM regulations and EPA's RMP rule.

Human factor deficiencies can make operations during non-routine modes extremely hazardous – since operators generally have less operating experience for non-routine modes, and these types of operations rely heavily on operator decision-making and tasks. In addition, there are usually less layers of protection in effect during non-routine operations. Analyzing procedure steps can identify steps where the operator is most likely to make mistakes and suggest ways to reduce risk of an accident scenario, ranging from adding hardware to improving management systems.

The approach outlined above applies equally to any hazard evaluation where the steps for a non-routine mode of operation are well defined (i.e., written), including PHAs of existing units, hazard evaluations during preliminary and detailed design phases of projects (for new/revised processes), and large or small management-of-change (MOC) hazard reviews.

Overview of Methodology for Hazard Evaluation of Non-Routine Modes of Operation

The hazard evaluation of non-routine modes of operation involves reviewing procedures using a HAZOP, simplified HAZOP, or What-if analysis to uncover potential accident scenarios associated with non-routine operations, for continuous or batch operations. As mentioned earlier, human error is more likely and more critical during non-routine operations. By analyzing procedural steps where human error is more likely, and where human error or component failure could lead to a consequence of interest, risk can be reduced. The objective for the hazard evaluation team is to evaluate the risk associated with skipping steps and performing steps incorrectly.

FMEA (Failure Mode Effects Analysis) cannot be applied to procedure-based deviations, unless you create a "human" component, in which case you have simply merged HAZOP deviations for "steps" into FMEA. Pre-Hazard Analysis (P_rHA) and other hazard evaluation methods are not applicable for accomplishing a detailed hazard evaluation of non-routine modes of operations.

Checklist of human factors issues can be very useful after the detailed hazard evaluation of deviations of steps (see an earlier paper[1] and also Guidelines for Hazard Evaluation Procedures[2]); they highlight where generic weaknesses may exist that can make errors during any mode of operation more likely, or that can make errors during maintenance more likely. Such human factors checklists are normally used at the end of the analysis, they can be done piecemeal during an analysis (on breaks from the meetings) by

individuals on the team, and then the results of each individual review can be discussed as a team at the end. As with scenarios uncovered during continuous modes of operation, the company may need to perform further analysis (including semi-quantitative analysis such as LOPA or HRA) to more fully address any unresolved or complex issues raised in the hazard evaluation of non-routine modes of operation.

Ranking/prioritizing procedures

To prevent wasting of valuable PHA team meeting time on low hazard tasks, the procedures should first be ranked by the teams according to hazard, based on complexity and consequences, if performed incorrectly. Those procedures which are considered most hazardous will be reviewed in detail, using stepwise deviation; in most cases 2 guideword, 'step skipped' or 'step performed incorrectly' deviations. In rare cases 7 guideword review can be performed (such as extremely hazardous activities or when otherwise required). Procedures with medium and low hazard designation will be analyzed less intensively using 'what if' method, which asks generally what can go wrong while using the procedure, in order to identify scenarios and consequences of interest. This method works best if the PHA team is very familiar with the task and possible scenarios.

3 CASE STUDIES

Scenarios identified during PHAs of Startup, Shutdown, and Online Maintenance

The following studies serve to provide a sample of errors types and consequences from recent PHAs performed by PII staff. This can be useful for those new to PSM, who may not be aware of certain types of mechanisms which are not found in normal operation which could potentially exist at their plants; scenarios that may have no protections currently.

The examples in the studies also provide grounds for those who already know they should be doing a more thorough analysis of non-continuous modes but need help justifying the extra time and monies required (beyond HAZOP of normal mode of operation); *though it should be noted again that for US companies and those covered by company standard, analysis of all modes is required, meaning compliance should be mandatory; not optional.*

UNITED (a SABIC affiliate)

In January 2019, PII completed a Redo PHA of the UNITED Ethylene Plant (Jubail, Saudi Arabia; a SABIC affiliate), which is to serve as that plant's new baseline PHA. This new hazard analysis included a PHA of Procedures, in compliance with SHEM 02.01, Rev 8, specifically section 5.12.2, which requires the PHA to consider all modes of operation, and section 5.12.2.9, that the PHA cover control system failures, including user interfaces and human factors [4]:

The meeting time was set at 19 days, with 14 days allocated for HAZOP of continuous/normal mode of operation and 5 days dedicated to PHA of Procedures (Step 3 of this paper) which was used to cover non-normal modes of operation: shutdown, startup, and online maintenance; and 3 hours for checklists reviews (such as Step 4 of this paper). For the continuous/normal mode of operation the plant was sectioned and analyzed in the typical HAZOP style, deviating each node's parameters as such as high and low deviations of level, flow, pressure, temperature, etc. as suitable for each node. The PHA of Procedures was done in the last 5 days, so the team was well aware of the major hazards and safeguards (at least for normal modes) relating to the equipment listed in each procedure. The procedure list was reviewed with the team on the first day to decide which procedures presented major process hazards (consequences of interest, in this case non-occupational hazards/serious injury or fatality consequences), so that more time could be focused on highest risks containing procedures. These procedures were typically more complex and usually longer in length. For these identified with significant process safety potential impact, the 2 Guideword Method was used and for those with less hazards, the What-If method was used. As usual, the goal was identifying specific scenarios of interest for those steps, capturing safeguards and safeguard steps in the documentation process. The few hours of the meetings included analysis using checklists to cover any hazards that weren't otherwise identified, and the team was given additional time outside of meeting to respond to the individual questions in both the Human Factors and Facility Siting Checklists, yielding an additional 3 recommendations deemed safety critical.

The PHA team identified many hazard during the meeting in both the normal mode HAZOP and the PHA of Procedures, listing 115 Safety Critical Recommendations (as defined by UNITED) and 7 Operability Recommendations (not safety critical, note that effective operation reduces risk of safety incidents as well). Of these Recommendations, 42 (or 36% of total) were identified during the PHA of Procedures; and while many of these were simple fixes needed to step order or wording, ***14 were in response to critical (high risk) consequences identified in the procedure analysis, requiring new or upgraded independent protection layers*** to bring the risk to acceptable levels. The scenarios and related **recommendations found during PHA of procedures accounted for 80% of risk reduction from the entire PHA**, amounting to about $200 million USD in risk reduction.

> *EXAMPLE:* During the procedure analysis for the acetylene reactors, it was discovered that there were no adequate safeguards against run-away reaction during start up, meaning the reactor shell could reasonably be expected to fail at some point due to human error during startup, which would likely cause a large explosion with the potential for multiple fatalities. The startup process required an extremely slow ramp-up in temperature (1°C per 5 minutes), and was controlled entirely by control room operators (by manually changing set points as they monitored for temperature spikes). In this case, the team recommended new logic and safety instrumented functions to protect against the catastrophic reactor failure and explosion.

EXAMPLE: During the procedure analysis for the both the propylene nd ethylene refrigeration systems, it was discovered that there were no safeguards against charging liquid refrigerant too soon, before the system is pressurized first with vapors to 2.5 barg and 12 barg, respectively. Since the equipment was normal carbon steel which is suspectable to low temperature embrittlement below -29 C, if the systems are not first pressurized as stated in the procedure, the systems could reach temperatures of -40 C and -89 C, respectively. In this case, the team recommended installing one to two new automatic block valves (XVs) to prevent introduction of liquid refrigerant into these systems, unless multiple pressure transmitters first confirm the pressure is the system is above the target pressure. The ratings recommended were SIL 3, since there were no other protections available. The alternative recommendation was to change the materials of construction to be able to withstand the cryogenic temperatures possible.

Phillips Polyethylene Plant 6, Pasadena, TX

In 1991-1992, a PHA was performed for the first of the rebuilt polyethylene plants at the Phillips 66 plant in Pasadena, TX. The accident there two years prior claimed 24 lives, injured hundreds of others, destroyed all three polyethylene plants, and cost Phillips an estimated $1.4 billion (in 1989 dollars). Following the investigation of the accident, one of the requirements of the settlement agreement between Phillips and the US government was to ensure the PHA of the rebuilt units addressed hazards during ***All modes of operation***.

The PHA team varied in size, but always included at least two operators. The team leader was a process engineer with 15 years of experience, who was also trained in human factors. The PHA first covered the continuous mode of operation for the approximately 200 nodes of equipment (from feed stock through pellet handling) using the “parametric deviation” form of HAZOP (and some What-If). Then, to complete the analysis of all modes of operation, the PHA team performed a step-by-step analysis of all steps of all startup and shutdown and online maintenance procedures (about 700 steps changed the state of the system and each of these steps were analyzed) using the 7 Guide Word HAZOP method (2 Guide Word analysis was not known to the team at this time). For deviations such as “operator skips a step,” the causes identified by the team included "the operator doing this step miscommunicates with the operator who performed steps earlier in the day and went to the wrong reset panel/switch in the field". In this example, an "other-than" error led to the "skip" error; so two errors occurred at once: the wrong switch was flipped and the correct switch was not flipped. Other causes included: “label not distinct enough” or “thinking/believing the previous operator completed this step.” The additional safeguards suggested by the PHA team sometimes lower the likelihood of the error by addressing a human factors weakness. But in many cases, the solution was a change to the hardware or instrumentation, including adding new interlocks (these would be called Safety Instrumented Functions today) and adding mechanical interlocks and installing larger relief valves. In a couple of cases, isolated

sections of the process were redesigned to lower the inherent risk, such as adding error-proofing (Poke Yoke) features.

The 7 Guide Word HAZOP of non-routine modes of operation took 2.5 weeks of meetings, 40 hours a week. This was in addition to the 3.5 weeks of meetings to complete the parametric deviation analysis HAZOP of the continuous (normal) mode of operation (as mentioned before, 200 nodes of equipment); some all this the Normal PHA or Traditional PHA, but that is a misnomer. *Note that if the team had known of and been trained in 2 Guide Word HAZOP for procedure steps, they likely would have chosen that for many of the tasks and it is estimated that the meeting time for analysis of non-routine procedures would have been reduced to less than 2 weeks, with little or no loss of thoroughness.* The completed PHA report was submitted to US OSHA for review and was approved almost immediately; OSHA particularly reviewed the analysis of all modes of operation and coverage of human factors.

The HRA shed light on new aspects of making errors and recovering from the errors during this task, but the HRA results did not result in changes to the process steps (at least not much), or the training program, or the human factors engineering, or the hardware/IPLs.

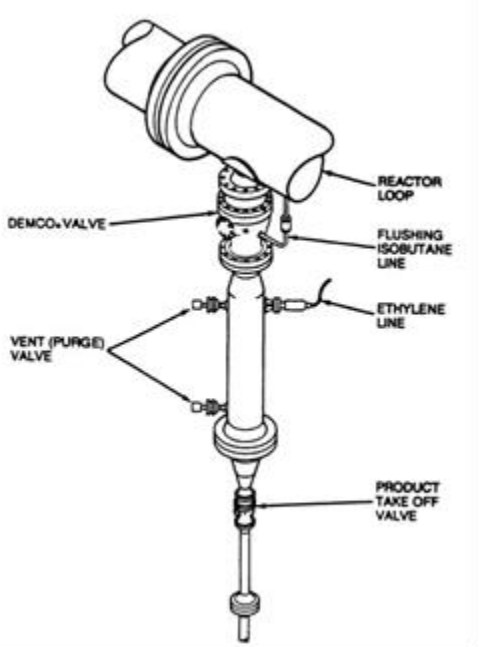

Figure 1: Typical Settling Leg Assembly for Phillips Polyethylene

In this instance, the HRA validated the results of the 7 Guide Word HAZOP but did not make new recommendations. The HAZOP of the procedures had already found the major accident scenarios and had already identified well enough the changes needed to reach tolerable risk.

> *EXAMPLE:* From the PHA of startup, shutdown, and online maintenance, then team found a great many scenarios missed by the PHA of continuous mode of

operation. For instance, the team recommended about 15% more safety instrumented functions Only for startup, shutdown, and online maintenance. And the PHA team found scenarios unique to startup that led to resizing of 7% of the PSVs in the polyethylene plants because these PSVs were too small for the limit case accident scenario, which was unique to startup.

Large OLEFIN Unit in Jubail, Saudi Arabia

In the fall of 2019, a PHA was performed on one of the largest olefins unit in the world, located in Saudi Arabia. This was a large scope PHA, which spanned more than 10 weeks of meetings and over 420 nodes (about equal in size to the PHA performed of the rebuilt Phillips Polyethylene plant, mentioned above). The scope required analysis of both continuous (normal HAZOP) and non-continuous mode of operations. About 3 weeks were devoted to PHA of procedures, or ¼ of total meeting time. The procedures were analyzed for each sub-unit of Olefin plant, including bringing equipment experts as needed, such as for rotating equipment and DCS personnel.

Of the 282 safety related recommendations, 130 originated from PHA of procedures (46%). It is estimated that the **total savings achieved from implementing recommendations which originated from PHA of Procedures is about 70 to 80% of the risk reduction from the entire PHA**; and these recommendations were valued at more than $300 million USD in risk reduction. The PHA of procedures was clearly worth the cost of 3 weeks of additional PHA team meeting time. Many more Operational improvement recs and procedure re-writes were also generated from the PHA of Procedures, which will also affect a large amount in cost reduction/efficiency improvement (78% of the operational improvement recommendations and about 80% of the operational risk reduction came from PHA of Procedures).

EXAMPLE: Based on the team's estimation it is possible that a process gas drier shell can fail if cooling cycle/safe temperature is not reached before putting the dryer at operational pressure. The risk of this human-error-based accident scenario was too high by several orders of magnitude. Therefore, the team recommended additional hardware or instrumentation safeguards to prevent pressurizing the dryer before the temperature is low enough (before the cooling cycle is completed) such as by installing a logic sequence that can't be bypassed, with a timer and temperature confirmation of shell/piping readiness for pressure, and count/duration of cooling volume.

EXAMPLE: The team recommended removing a line that is currently not in use (and is blinded) that runs from a benzene column reflux drum to the firebox of the fired heater upstream of the benzene catalytic reactor to prevent anyone from using the line in the future. Liquid is no longer burned in this heater and if the plant staff tried to burn this waste benzene in the heater in the future, it would introduce significant risk to the heater operation. It is better to remove the capability to use this line to eliminate this capability.

EXAMPLE: The team recommended venting the seal drain pot system continuously to the flare system. Currently, operations switches between venting to the flare and venting to the atmosphere, depending on the mode of operation, and there are multiple human errors that could leave the vent inadvertently open to the atmosphere when a highly volatile material is being drained to the system..

FORMALDHYE PLANT at CHEMANOL

In the summer of 2019, a PHA was performed on one of the formaldehyde plants at CHEMANOL, in Saudi Arabia. The scope required analysis of both continuous (normal HAZOP) and non-continuous mode of operations, and PHA of procedures accounted for about 25% of total meeting time.

It is estimated that the **total savings achieved from implementing recommendations which originated from PHA of Procedures is about 50% of the risk reduction from the entire PHA**.

EXAMPLE: Based on PHA of procedures for startup of the plant, the team recommended adding an interlock/IPL to ensure that the Catalytic Incinerator is lined up correctly and at proper operating temperature, and ensure the vent line to atmosphere is closed, as a permissive for bringing the formaldehyde plant fully online. Otherwise there will be potential environmental concerns from Incinerator outlet gas to atmosphere, as well as risk of leaving the vent open before the Incinerator leading to a potential explosive atmosphere in the reactors. A captive key system may provide the best option for protection, requiring a proper sequence of valves be opened and closed during the startup procedure.

General Observation from the Case Studies

As the data suggests, the relative risk reduction from recommendations related to startup, shutdown, and online maintenance accounts for 50 to 80% of the risk reduction from all recommendations from a PHA.

4 Conclusions

While it may be true that "To err is human", the frequency and consequences of such errors can be effectively reduced with a well-designed strategy for analyzing risk of non-routine operating modes.

PHAs of non-routine operating procedures are an extremely powerful tool for uncovering deficiencies that can lead to human errors and for uncovering accident scenarios during all modes of operation. Examples and estimates of recommendations from many PHAs

listed in this paper show the additional savings (cost avoidance) that can be achieved from PHA of procedures, especially considering the marginal increase in cost of the overall PHA given scopes cover non-continuous modes with procedure analysis. The savings more often outweigh those possible from PHA of continuous modes. Identifying related scenarios and safeguarding against them could mean protecting companies from the worst-case disasters, those where entire plants and billions of dollars could be at stake. *Strategic loss prevention should therefore require every PHA, from design phase to revalidation, consider adding procedure analysis to overall scope of the PHA*; and prudent managers at *every level* need to consider the benefits of finding every scenario possible to minimize the exposure of risks in their areas of responsibility.

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