Opportunities for Proactive Root Cause Analysis in Integrity Management

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Abstract

This paper presents the results of a review of recent major pipeline failure investigations by the National Transportation Safety Board (NTSB). Investigations conducted after loss-of-containment failures reveal opportunities for root cause analyses that, if conducted after the failure of a single threat barrier, could potentially have prevented the later loss-of-containment failure. Recognizing these opportunities proactively rather than in hindsight is challenging. This study provides insight into the factors that emerge from the recent major pipeline failure investigations reviewed that an organization can influence to support the proactive identification and prioritization of single-barrier failures for root cause analysis and corrective action.

Benchmarking RCA for Pipeline Integrity Management

Root cause analysis (RCA) is a broadly defined method of problem solving used across many industries. RCA is commonly used as an umbrella term to indicate both RCA in a strict sense (an identification of the cause or causes of a problem) and the actions taken to address those causes and prevent recurrence of the problem. (Wikipedia contributors, 2024) When referred to as distinct from RCA as strictly identification of causes, these actions are called corrective actions (CA).

While numerous publications, systems, processes, and methods exist for RCA generally, the pipeline industry does not have a sole source for RCA definitions and requirements. The following subsections provide a review of the status of RCA standards for the pipeline integrity management industry and sources for the benchmark RCA concepts on which this study is based, especially the idea that RCA for single-barrier failures is important.

Regulatory Requirements

Standards for RCA are not specified in federal pipeline regulations. The requirements in 49 CFR Part 191 and 49 CFR Part 195 for incident or accident reporting point to forms which categorize and emphasize reporting of "apparent causes," also known as direct causes, but leave secondary, contributing, and root causes to be selected from a list and described in a narrative, with no requirements specified for the process or methods used to arrive at the cause or definitions provided for these categories of causes. The forms require some inputs that implicitly indicate what PHMSA considers to be evidence for each apparent cause subcategory. (PHMSA, 2023)

The Risk Management Bow-Tie Concept

The bow-tie risk model, shown in **Figure 1**, is at the core of much of how we approach integrity management. On the left are the latent hazards and threats in a system – think of the nine threats described in ASME B31.8S. Moving to the right are the triggers that activate the threats. Next are

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the preventative, or proactive barriers. These are all the things we do to try to reduce the frequency or likelihood of a pipeline failure. In the center is the hazardous event. In our case, this is a loss of containment on the line. To the right of the leak or rupture are the mitigative, or reactive, barriers that we put in place to reduce the consequences of the hazardous event after it has happened.

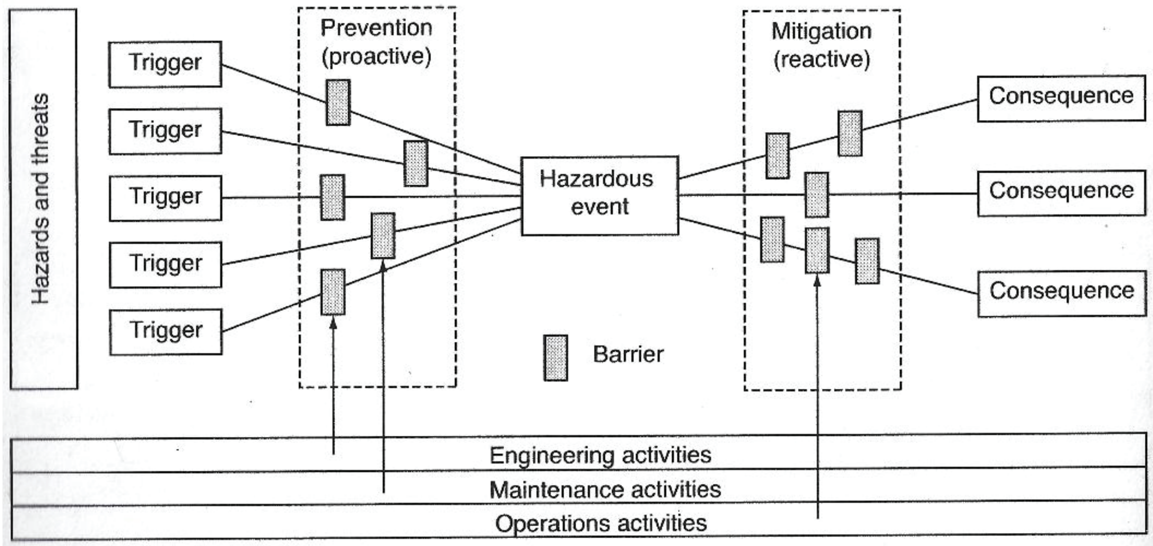

Figure 1: Risk Management Bow-Tie (Rausand, 2011)

The Barrier Failure Mode Concept

The barrier failure mode diagram, shown in **Figure 2**, illustrates the idea that none of the multiple barriers put in place to prevent threats or to mitigate consequences is 100% effective. Most of the time, activated threats are caught by one of the barriers. This is the objective. However, if gaps align, a threat can make it past every barrier put in its path.

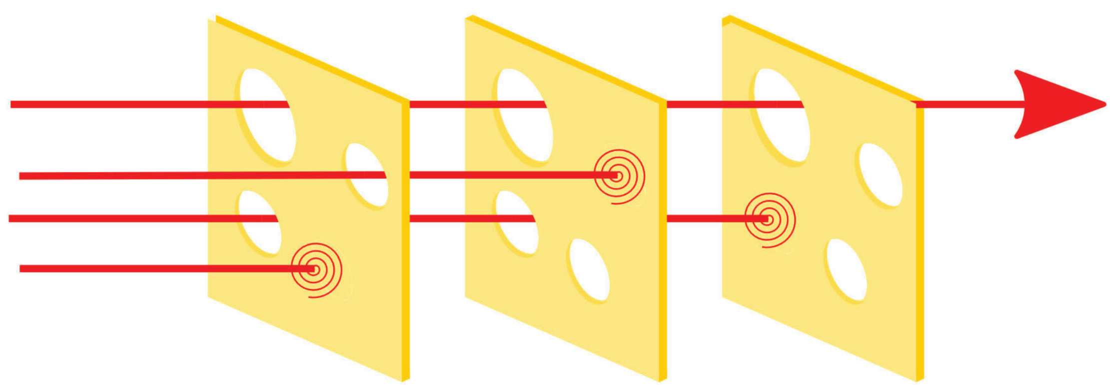

Figure 2: Barrier Failure Mode (Swiss Cheese) (Aveling, 2023)

Definitions

This study utilizes the following definitions from Conger & Elsea. (Conger & Elsea, 2023)

- Root cause:

    - The incident would not have occurred if this cause were not present,
    - The cause is not the symptom of any other cause, and
    - Fixing the cause will prevent the same problem from happening again.
- Contributing cause or causal factor: Causes that by themselves would not create the problem but are important enough to be recognized as needing corrective action. Causal factors are those actions, conditions, or events that directly or indirectly influence the outcome of a situation or problem. Contributing causes are sometimes referred to as causal factors.
- Direct cause: The final action or condition that brings about the failure, incident, accident, or problem.

Pipeline Safety Management System Standards

Voluntary standard requirements for pipeline safety management system are provided in API Recommended Practice 1173, Pipeline Safety Management Systems. Section 9 covers incident investigation, evaluation, and lessons learned. This section requires a procedure for "investigating incidents and near-misses that led, or could have led, to an incident with serious consequences." The section also include requires that the pipeline operator "establish a process to periodically reevaluate past incident investigations of high consequence and significant near-miss events" that includes "evaluating the effectiveness of organizational learning from the know lessons learned." (API, 2015)

General Standards

Voluntary standard requirements for quality management systems, which include requirements for RCA, are provided in International Standard ISO 9001. ISO 9001 section 10.2 Nonconformity and corrective action, clause 10.2.1 states that:

> When a nonconformity occurs, including any arising from complaints, the organization shall:
>
> a) react to the nonconformity and, as applicable:
>
> 1) take action to control and correct it;
>
> 2) deal with the consequences;
>
> b) evaluate the need for action to eliminate the cause(s) of the nonconformity, in order that it does not recur or occur elsewhere, by:
>
> 1) reviewing and analysing the nonconformity;
>
> 2) determining the causes of the nonconformity;
>
> 3) determining if similar nonconformities exist, or could potentially occur;
>
> c) implement any action needed;
>
> d) review the effectiveness of any corrective action taken;
>
> e) update risks and opportunities determined during planning, if necessary;
>
> f) make changes to the quality management system, if necessary.
>
> Corrective actions shall be appropriate to the effects of the nonconformities encountered.

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(ISO 9001, 2015)

ISO 9000, which contains the definitions for ISO 9001, states in clauses 3.6.9, 3.7.11, and 3.12.2, respectively, that:

- a nonconformity is a "non-fulfilment of a requirement,"
- effectiveness is the "extent to which planned activities are realized and planned results are achieved," and
- a corrective action is an "action to eliminate the cause of a nonconformity and to prevent recurrence." (ISO 9000, 2015)

Industry-Adjacent Guidance

The U.S. Department of Energy (DOE) provides guidance for RCA in DOE-NE-STD-1004-92 Root Cause Analysis Guidance Document. This guidance is intended for use by the DOE for DOE-owned and -operated facilities, but it applies to facilities that present similar risk levels to pipelines and is general enough to reflect the common need to effectively identify and address the causes of problems.

The DOE categorizes occurrences that require RCA as emergencies, unusual occurrences, and off-normal occurrences. The DOE's definitions of unusual occurrences and off-normal occurrences show that it intends RCA to be used for events with potential impacts (not just events with significant consequences): "Unusual Occurrences. An unusual occurrence is a non-emergency occurrence that has significant impact or potential for impact on safety, environment, health, security, or operations." They "Involve significant degradation of safety systems or environmental, safety, or health conditions" "Off-Normal Occurrences. Off-normal occurrences are abnormal or unplanned events or conditions that adversely affect, potentially affect, or are indicative of degradation in, the safety, security, environmental or health protection performance or operation of a facility." (DOE, 1990) In addition, the DOE advises that "The level of effort expended should be based on the significance attached to the occurrence. Most off-normal occurrences need only a scaled-down effort while most emergency occurrences should be investigated using one or more of the formal analytical models." (DOE, 2010)

The DOE defines a condition – problem that forms the starting point for a RCA – as:

> Any as-found state, whether or not resulting from an event, that may have adverse safety, health, quality assurance, security, operational, or environmental implications. A [co]ndition is usually programmatic in nature; for example, an (existing) error in analysis or calculation, an anomaly associated with (resulting from) design or performance, or an item indicating a weakness in the management process are all conditions. (DOE, 2010)

Benchmark RCA Concepts

The motivation for this study rests on the concept that RCA (including CA) for single-barrier failures is important. RCA for incidents with significant consequences – those that "break the camel's back" – is essential. However, as shown in the subsections above, RCA is also intended to be applied to conditions and events that do not result in significant consequences, but which could potentially contribute or lead to such an event I.e., straws that add to the load on the "camel's back" without breaking it.

When barriers fail in combination or independently – even if the threat does not reach the target – the cause of the failure can be corrected by restoring, replacing, improving, or augmenting the barrier or barriers that failed. RCA can be used to understand which barriers failed, why they failed, and to identify what actions can be taken to prevent them from failing again. As indicated by API 1173, ISO 9001, and the DOE, RCA it is most effective when used regularly on non-emergency breaches. I.e., when single- or multiple-barrier failures did not reach their target. This provides the opportunity to stop threats from breaching barriers again using the same pathways.

Also essential to the observations of this study is the principle found in API 1173, ISO 9001, and the DOE guidance that corrective actions must be completely implemented and reviewed for effectiveness prior to closure.

Study Methods

Selecting Pipeline Investigation Reports

The authors reviewed the NTSB's completed investigation summaries for pipeline incidents from 2010 through the present. The authors narrowed the cases for consideration to those with NTSB "What We Found" summaries that indicated multiple barrier failures leading up to the incident and eliminated cases whose scope was limited to distribution system or third-party damage issues alone (except for one instructive distribution incident). The investigations selected for close review are listed in **Table 1**.

Table 1: Investigations Selected for Close Review

Title of Investigation	Year of Incident
Pipeline Rupture and Crude Oil Release	2022
Natural Gas-Fueled Explosion and Fire	2021
Natural Gas–Fueled Explosion During Routine Maintenance	2021
Natural Gas Pipeline Rupture and Fire	2020
Natural Gas Transmission Pipeline Rupture and Fire	2019
Natural Gas-Fueled Explosion	2018
Pipeline Rupture	2017

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Title of Investigation	Year of Incident
Anhydrous Ammonia Release	2016
Petroleum Product Leak	2015
Large Crude Oil Spill from Damaged Pipeline	2010
Natural Gas Transmission Pipeline Rupture and Fire	2010
Hazardous Liquid Pipeline Rupture and Release	2010
Natural Gas Pipeline Excavation Damage, Rupture, and Fire	2010

Pipeline Investigation Report Reviews

The authors reviewed the NTSB's Pipeline Investigation Reports, seeking evidence of threat barriers that had failed repeatedly; specifically, barriers whose failure contributed to the incident and which had also failed at some time prior to the incident without significant consequences. The following subsections summarize the findings of the reviews.

2022 Pipeline Rupture and Crude Oil Release (NTSB, 2023)

A 22-inch diameter crude oil pipeline ruptured at a girth weld in Illinois, resulting in the release of about 3,500 barrels of crude oil, some of which entered a creek. No injuries or fatalities occurred as a result of the rupture.

The operator had documented multiple indications of slope instability near the rupture location dating back to 2012, when it identified erosion along the creek bank. In 2014, the operator installed concrete revetment mats to stabilize the bank. In the years that followed, caliper and Inertial Mapping Unit (IMU) assessments, strain analyses, and risk assessments indicated that the site continued to experience slope instability and that further reinforcement of the creek bank was necessary. In 2017, the operator repaired the previously installed revetment mats and added more mats and riprap. The operator did not take further action to stabilize the creek bank after 2017.

The operator conducted IMU assessments in 2018 and 2021 but did not install strain monitoring as recommended by the 2018 IMU assessment and bending strain analysis or pursue finite element assessments, stress relief, pipeline movement assessments, or pipeline replacement before the accident. A 2021 strain investigation based on the 2018 IMU data indicated that slope instability was still present and recommended monitoring and bank reinforcement, but the operator did not do this by the time of the accident. The operator had planned to conduct a bending strain and pipeline movement analysis in 2022 using the 2021 IMU data, but the rupture happened before the operator requested the strain report.

Post-accident analyses showed that the operator's corrective actions were not effective in protecting the pipeline from external slope instability loads. The operator failed to follow up adequately on the effectiveness of their corrective actions (bank stabilization measures). Data was available and

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could have been used to reveal that the corrective action was not effective. This was a missed opportunity to use prompt corrective action effectiveness review to ensure that the root cause(s) of the problem had been fully identified and addressed.

2021 Natural Gas-Fueled Explosion and Fire (NTSB, 2023)

A 30-inch-diameter natural gas transmission pipeline ruptured in a rural area of Arizona. The rupture resulted in the release of natural gas that ignited and exploded. The explosion and gas-fed fire destroyed a farmhouse, killing two of the three occupants and seriously injuring the other.

A pipeline data report from 2011 for a dig approximately 375 feet from the rupture location noted that the coating type listed as fusion-bonded epoxy was incorrect and the actual coating type was spiral wrap tape. This operator did not update its GIS with this information. This was a missed opportunity to recognize a problem, perform root cause analysis to determine the extent and cause of the incorrect data, and to correct it.

The NTSB calculated the Potential Impact Radius (PIR) for the rupture site to be 636 feet, but physical evidence showed that damage to the surrounding vegetation was found up to 878 feet from the rupture. The NTSB had noted discrepancies between the calculated PIR and evidence at accident sites before. This prompted the NTSB to issue a recommendation to PHMSA to “Revise the calculation methodology used in your regulations to determine the potential impact radius of a pipeline rupture based on the accident data and human response data discussed in this report.” This was a missed opportunity by the NTSB to evaluate the root cause of previous impact radius discrepancies and to determine and recommend this corrective action earlier.

2021 Natural Gas–Fueled Explosion During Routine Maintenance (NTSB, 2022)

A natural gas explosion occurred in Texas while workers were removing a pig insertion tool from a launcher during a series of in-line inspections. The explosion was directed through the open launcher door, ejecting the pig from the launcher, injuring two of the workers and killing two more.

Although each of the operator’s workers had performed pigging work for no fewer than 8 years, they were not aware of the operator’s pigging-specific procedures, which were formally documented in its Pipeline Integrity Management Plan in 2019. This represents a missed opportunity by management for over two years to recognize the fact that front line workers were not complying with procedures and to perform a root cause analysis and implement corrective actions.

On June 21, 2021, workers began a series of in-line inspections. The crew utilized a portable flaring system. While loading the first pig, workers suspected that the mainline valve was leaking when the flare did not extinguish. The workers adjusted the mainline valve and found a position where the leak reduced to the point that the flare extinguished. They marked the position on the valve and

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the flare extinguishing as the workers thought it should during subsequent runs. This was a missed opportunity for the workers to perform a root cause analysis on the leaking valve and solve the problem permanently instead of applying a temporary and unreliable fix. It was also a missed opportunity for the workers to adequately evaluate the effectiveness of their fix.

2020 Natural Gas Pipeline Rupture and Fire (NTSB, 2022)

A 30-inch diameter interstate natural gas transmission pipeline ruptured in Kentucky, resulting in a fire. The rupture occurred at a hillside location that was previously identified for geotechnical monitoring because of an active landslide. The lead-up to this incident involved multiple attempts to resolve a problem followed up by attempts to evaluate the effectiveness of the corrective actions. While the threat ultimately outpaced the root cause analysis, corrective action, and evaluation cycle, the authors did not identify any proactive RCA opportunities that were missed by the operator.

2019 Natural Gas Transmission Pipeline Rupture and Fire (NTSB, 2022)

A 30-inch natural gas transmission pipeline ruptured at crack associated with a hard spot in Kentucky, releasing natural gas that ignited. The accident resulted in 1 fatality, 6 injuries, and the evacuation of over 75 people. Five residences were destroyed by resulting structure fires, and an additional 14 were damaged. A nearby railroad track was also damaged, and over 30 acres of land were burned.

Despite performing a root cause analysis on an emergency shutdown earlier in 2019 and identifying a lack of knowledge displayed by a compressor station operator, the company missed the opportunity to resolve this root cause in violation of its own qualification program. Addressing the lack of knowledge may have reduced a delay in the operator's response on the morning of the later incident.

The NTSB concluded that both the former and current operator of the pipeline did not "effectively identify, investigate, or manage the impact of a gas flow reversal project on the level of hydrogen evolution in the pipeline surface," which contributed to the failure. The NTSB also concluded that "comprehensive management of the changes resulting from the gas flow reversal project would have identified and addressed risks such as coating damage, ineffective cathodic protection, and suitability of corrosion control equipment and infrastructure that led to hydrogen-induced cracking in the pipeline surface."

After the incident, the NTSB obtained a re-analysis of 2011 Hard Spot Magnetic Flux Leakage (HSMFL) ILI data that showed a total of 441 hard spots. Of the 441 hard spot calls, 9 were located in the pipeline joint that ruptured, including 2 at the rupture origin that corresponded with the hard spot at the fracture origin. The ILI vendor reported that the discrepancy in the number of hard spots called in 2011 (16 hard spots) and 2019 (441 hard spots) was due to improvements in the computer hardware and software used to analyze the data. The pipeline operator missed an

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opportunity to re-evaluate existing data to improve its understanding of the extent of a problematic condition which it knew existed on the pipeline.

2018 Natural Gas-Fueled Explosion (NTSB, 2021)

A natural gas-fueled explosion occurred in a home in Texas, injuring all five occupants, one fatally. The residence sustained major structural damage. Following the explosion, the NTSB located a through-wall crack in the 71-year-old natural gas main that served the residence and positive gas measurements leading from the crack to the residence. In the 2 days before this explosion, two gas-related incidents occurred on the same block at houses that were served by the same natural gas main, each resulting in significant structural damage and burn injuries to one occupant.

Both the Fire-Rescue Department and the gas main operator failed to adequately investigate and identify the causes of the two incidents that occurred in the days immediately preceding the explosion. The Fire-Rescue Department arson investigators and operator technicians did not effectively investigate, communicate, or collaborate to determine the cause of either incident. The operator also did not gather enough evidence to determine if gas migrated from their piping and fueled the first two incidents. These two prior incidents were both missed opportunities to apply root cause analysis to identify and address the cause that apparently led to all three incidents.

2017 Pipeline Rupture (NTSB, 2018)

A pipeline ruptured between pump stations in South Dakota. The OCC detected the leak and shut down the pipeline. The spill comprised about 5,000 barrels of crude oil. The pipe failed at a fatigue crack, that grew and extended in-service to a critical size, and which likely originated from mechanical damage to the pipe by a metal-tracked vehicle.

The likely construction equipment contact with the pipe indicates a significant missed opportunity by construction oversight personnel to recognize the issues and address it immediately. It could have been identified a near miss, with root cause analyses resulting in discovery and remediation of the mechanical damage.

2016 Anhydrous Ammonia Release (NTSB, 2020)

An 8-inch-diameter pipeline ruptured and released 2,587 barrels of liquid anhydrous ammonia in Nebraska. The ammonia vaporized and produced a toxic plume. A local resident who left his home to investigate the accident scene died of respiratory failure and two people sustained minor injuries. 29 households were evacuated. A main roadway in the area was closed for several days. The direct cause of the rupture was probably corrosion fatigue cracks that grew and coalesced beneath disbonded polyethylene tape coating.

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From the pipeline controller's response to the initial leak indication, it is apparent that the control center had experienced previous issues with false alarms from the leak detection system. These apparent previous issues were a missed opportunity for RCA, which could have reduced false alarms and put the controller in a better position to respond adequately to the true alarm.

The segment had experienced multiple leaks in the past from various direct causes. It appears that the root causes of the leaks were neither identified nor corrected, especially in the case of pinhole leaks, of which there were multiple. These leaks were, possibly, missed RCA opportunities.

The operator missed an opportunity to perform RCA and determine the extent of a problematic condition by failing to perform a crack detection ILI after spike pressure tests caused five leaks, two of which were associated with Stress Corrosion Cracking (SCC).

2015 Petroleum Product Leak (NTSB, 2017)

A 32-inch-diameter pipeline leak occurred in a high consequence area in Virginia. The operator estimated that 4,000 gallons of product were released and estimated the cost of accident-related expenses at $16.5 million. The direct cause of the leak was probably a corrosion fatigue crack that developed at a dent due to residual and operational stress and exposure to the underground environment.

Early in the County’s response to reports of a gasoline odor, the fire marshal’s office asked the operator to determine if the company’s pipelines could be the source of the odor. Two of the operator’s right-of-way inspectors contacted the operator’s Control Center to determine if there were abnormalities in the line pressures. The Control Center told them the line pressures were normal. The inspectors examined the right-of-way and told the fire department incident commander that there was no evidence of a leak – including an odor, dead vegetation, or gasoline on any pavement or in nearby water retention ponds, and the inspectors left the area.

Four other leaks occurred on the operator’s pipeline system that were undetectable in the SCADA system. One leak occurred about 5 months before the incident in question, and three more occurred less than 6 months after the incident.

The superficial investigation and exit by the inspectors and the unwarranted confidence of the Control Center (given the recent undetected leak) were missed opportunities for the operator to assist the emergency responders with an RCA that determined where the gasoline odor was originating from.

2010 Large Crude Oil Spill from Damaged Pipeline (NTSB, 2010)

A 34-inch-diameter pipeline leaked beneath the street pavement in Illinois, releasing about 6,430 barrels of heavy crude oil. Damages totaled about $46.6 million. The direct cause of the pipeline

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failure was probably erosion caused by water jet impingement from a leaking 6-inch diameter water pipe 5 inches below the oil pipeline. The authors did not identify any missed RCA opportunities associated with this incident.

2010 Natural Gas Transmission Pipeline Rupture and Fire (NTSB, 2011)

A 30-inch-diameter segment of an intrastate natural gas transmission pipeline ruptured in a residential area in California. The released natural gas ignited, resulting in a fire that destroyed 38 homes and damaged 70. Eight people were killed, many were injured, and many more were evacuated from the area. The probable direct cause of the pipeline failure was a crack that initiated and propagated through wall in the long seam of a short section of replacement "pipe" that had not been manufactured in accordance with a line pipe standard.

The NTSB concluded that the operator's multiple, recurring deficiencies were evidence of a systemic problem. This was a high-level missed opportunity for organizational RCA and corrective action.

The NTSB had long been concerned about the lack of standards for rapid shutdown and the lack of requirements for Automatic Shutdown Valves (ASVs) or Remote-Control Valves (RCVs) in High Consequence Areas (HCAs). The NTSB made related recommendations in 1971 and 1995. The NTSB classified the 1995 recommendation as "Closed—Acceptable Action," in 2004, believing the integrity management rulemaking would lead to a more widespread use of ASVs and RCVs. It did not, but it seems that there was no follow-up on the effectiveness of the recommended corrective action. This was a missed opportunity by the NTSB and regulators to evaluate why the corrective action did not achieve its desired effect.

Regarding the operator's gas transmission integrity management program:

- It was based on a GIS that contained incomplete and inaccurate pipeline information. This was a major missed opportunity for RCA corrective action, especially because at least some of the deficiencies were known by some personnel.
- It significantly understated the threats due to external corrosion and design and manufacturing, overstated the threats due to third-party damage and ground movement, and did not consider known longitudinal seam cracks dating back to the 1948 construction and at least one longitudinal seam leak in its identification and assessment procedures. This was a missed opportunity to benefit from lessons learned from historical RCA.
- It considered known manufacturing- and construction-related defects to be stable even though the pipeline had not been pressure tested to at least 1.25 times its MAOP. This was a missed opportunity to learn from RCA performed by other operators.

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- It included self-assessments that were superficial and resulted in no improvements to the program. Some corrective actions that were identified were not driven through to completion promptly.

The NTSB concluded that the character and quality of the operator's operation indicated that the pipeline rupture was an organizational accident, and that the operator "did not effectively utilize its resources to define, implement, train, and test proactive management controls to ensure the operational and sustainable safety of its pipelines." This undoubtedly captured a multitude of missed opportunities for RCA and corrective action.

The operator knew of many of the organizational deficiencies as a result of two previous pipeline incidents in 1981 and 2008. These incidents represent two missed opportunities to apply RCA to critically examine all components of its pipeline system to identify and manage hazards and to prepare its emergency response procedures. Both prior incidents bear striking resemblances to the 2010 incident. The 2008 incident involved the inappropriate installation of pipe that was not intended for operational use and did not meet applicable specifications. The operator's response was inadequate; initially dispatching an unqualified person and causing a delay in dispatching a properly trained and equipped technician. The 1981 gas pipeline leak involved inaccurate record-keeping, the dispatch of first responders who were not trained or equipped to close valves, and unacceptable delays in shutting down the pipeline.

The California Public Utilities Commission (CPUC) did not follow up on a 2005 audit finding that the operator did not have a required process to evaluate the use of ASVs and RCVs. The operator submitted a memorandum, but the CPUC apparently did not evaluate the adequacy of the operator's response, or at least did not recognize the "flawed analysis that concluded the use of ASVs would have little effect on increasing safety or protecting property." This was a missed opportunity for the CPUC to get to the root of the operator's mistaken approach and provide correction.

2010 Hazardous Liquid Pipeline Rupture and Release (NTSB, 2012)

A 30-inch-diameter pipeline ruptured in a wetland in Michigan. The rupture occurred during the last stages of a planned shutdown and was not discovered or addressed for over 17 hours. During the time lapse, the operator twice pumped additional oil into the line during two startups; the total release was estimated to be 843,444 gallons of crude oil. The oil saturated the surrounding wetlands and flowed into a creek and a river. Local residents self-evacuated, and the environment was negatively affected. Cleanup costs exceeded $1.2 billion. About 320 people reported symptoms consistent with crude oil exposure. There were no fatalities. The direct cause of the rupture was probably "corrosion fatigue cracks that grew and coalesced from crack and corrosion defects under disbonded polyethylene tape coating."

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Based on the operator's prior crude oil release history, it missed opportunities to investigate and address significant weaknesses in its integrity management program.

At the time of the incident PHMSA expected pipeline operators to excavate all crack features, but PHMSA did not issue any findings about the operator's methods, which allowed crack features to remain un-remediated, in previous inspections. This was a missed opportunity by PHMSA to recognize, investigate, and correct a misunderstanding or noncompliance.

Canada's Transportation Safety Board (TSB) investigated a rupture involving another of the operator's lines that resulted in a release of about 200,000 gallons of crude oil in 2007. The pipe failure was very similar to the 2010 incident in question. Although the TSB identified deficiencies in the operator's crack failure pressure calculation inputs, the operator did not correct the deficiencies prior to the 2010 incident.

In 1991, the operator experienced a rupture and release that spilled 1.7 million gallons of crude oil in Minnesota. The failure mechanism was similar to the incident in question. During the 1991 and 2010 incidents, personnel in the Control Center interpreted the alarms and indications to be associated with column separation and instrument or software error and continued to pump oil into the ruptured lines for more than an hour until the leaks were recognized. In 1991, the operator stated to PHMSA that it had revised its procedures to state that "If an operator experiences pressure or flow abnormalities or unexplainable changes in line conditions for which a reason cannot be established within a 10-minute period, the line shall be shut down, isolated, and evaluated until the situation is verified and or [sic] corrected." By 2010, the NTSB states that "control center operators, shift leads, and their supervisors believed that it was acceptable to not adhere to the 10-minute restriction when given the "right" circumstances." This culture of acceptance and comfort with deviation from procedures was a missed opportunity for RCA and corrective action.

A 2005 NTSB report concluded that leak detection technology would enhance control center operators' "ability to detect large spills, increase the likelihood of spill detection, and reduce the response time to large spills." The eventual result was the control center management rule contained in 49 CFR Parts 192 and 195. After this rule went into effect, the NTSB closed the related recommendations and classified them, "Closed—Acceptable Action." The NTSB missed an opportunity to review the effectiveness of its recommended corrective actions and determine if they achieved the intended results.

After 2003 and 2006 regulatory compliance inspections, PHMSA stated that the operator's "[integrity management]-related groups operate semi-independently, and it is not clear that overall integration of knowledge and data is occurring on a consistent basis." However, PHMSA did not conduct any further follow-up or verification of any corrective actions by the operator. PHMSA also failed to obtain justification from the operator for choosing a lower safety margin for crack

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excavation criteria than for corrosion excavation criteria. PHMSA missed opportunities to expose the roots of some of the operator's problems and spur effective corrective action.

After the operator changed its crack failure pressure calculation process, it missed an opportunity to revisit the 2005 in-line inspection data for the line that failed in 2010 – an opportunity to use existing data to improve its understanding of the extent of a hazardous condition.

The NTSB recognized missed opportunities for RCA when it stated that the operator's "response to past integrity management related accidents focused only on the proximate cause, without a systematic examination of company actions, policies, and procedures that may have been involved."

The NTSB also stated that:

> Taken together, the evidence suggests that the … accident was the result not of isolated deficiencies in the company's integrity management system, its control center oversight, its PAP, or its post-accident emergency response activities, but rather of an approach to safety that did not adequately address the combined risks. By focusing on only the immediate cause of each incident, the company failed to look for and to determine patterns or underlying factors. Some of the underlying factors in this accident began many years earlier and converged with more recent changes only at the time of rupture.
>
> Although [the operator] met PHMSA regulations in its pipeline operations, the evidence indicates that the company had multiple opportunities to identify and to address safety hazards before this accident occurred, but it failed to do so. Even the response to a safety culture assessment conducted following the … accident in 2007, which resulted in the creation of the position of director of safety culture, was insufficient. This director was tasked only with examining field safety of pipeline operations. Although [the operator] had implemented what it referred to as a health and safety management system, the system only partially met the standards of an SMS. For example, it addressed only on-site safety, not pipeline operations. Control center errors were identified as employee-caused and were not considered system deficiencies, contrary to SMS guidelines. Had the company implemented and maintained a comprehensive SMS, it would have focused not only on field operations safety, but also would have incorporated control center operations, pipeline integrity management, and post-accident response plans and a comprehensive continuous examination of the safety of pipeline operations.

These conclusions by the NTSB indicate significant missed opportunities to build RCA and effective corrective actions into the culture and systems of the company.

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2010 Natural Gas Pipeline Excavation Damage, Rupture, and Fire (NTSB, 2010)

A truck-mounted power auger struck and punctured a 36-inch diameter natural gas transmission pipeline. The accident occurred in Texas. The natural gas ignited and killed the auger operator and burned six workers. Total property damage and clean-up costs were over $1 million.

The end-point location of the one-call ticket driving directions received by the pipeline operator resulted in a missed connection with the auger contractor and a misunderstanding of where the work would be performed. This was a missed opportunity for the operator to determine what had gone wrong with the one-call ticket and address the problem.

The operator responded to a one-call ticket 2 days late. This was a missed opportunity for a connection with the contractor as well as a missed opportunity to perform RCA on the missed deadline and take corrective action.

Results

Several key factors that lead to missed opportunities to identify and address root causes emerged from the reviews of the recent major pipeline failure investigations. These factors are described in the subsections below.

System and Information Silos

The ability to recognize single-barrier breaches seems to have been hindered by a lack of awareness in individuals and teams of how their limited responsibilities contributed to and affected the broader integrity management or operational systems of which they were a part. This siloing also seemed to lead to the assumption that "someone else will take care of it," or that "the answer will come from someone else." Also, limited access to and use of data seemed to lead to ignorance about its purpose and complacency about its quality.

"That's just the way things are…"

Accepting a suboptimal reality seemed to be much easier for people than putting in the work required make things right.

Reality vs. Model

In the digital twin, hydraulic, and fracture models encountered in this study, people failed to connect models with reality, failed to recognize model limitations and failures, and failed to improve models after they recognized disconnects with reality. Models seemed to be easy entities on which to place responsibility and blame.

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Data Age Bias

The study revealed multiple missed opportunities to turn old data into valuable information about current threats using new or improved analyses. It seemed that existing data was easy to forget, even when it could have had a significant positive impact. Old data may also be easy for people to forget when they are constantly and actively engaged in the process of collecting new data.

Correct Action Bias

In multiple instances, organizations seemed to assume that the corrective actions they recommended or implemented would be adequate. Again and again, they failed to evaluate the corrective actions for effectiveness.

Let Sleeping Dogs Lie

Another proverb comes to mind here as well: "Don't rock the boat." During investigations, people left stones unturned, even when there seemed to be recognition that there was likely something important hidden underneath them. Finding the root takes much more work than stopping at a proximate cause.

Denial

In the absence of clear or even incontrovertible evidence, people seemed to assume what was most convenient for themselves, even when significant indicators of problems were present.

Implications

Based on the findings of this study leaders within organizations should be able to improve the proactive identification and prioritization of single-barrier failures for RCA and corrective action through:

1. Measures to enhance awareness and understanding of how individual's and team's limited responsibilities contribute to and affect the systems they are part of.
2. Measures to improve awareness of all the barriers in place within the organization and what breaches of those barriers look like.
3. Measures to increase breadth and depth of interaction with data and to challenge or test the data's quality.
4. Measures to make systems easier to improve and to make people less comfortable accepting "the way things are" when things are wrong.
5. Measures to improve people's understanding of the models they use – their bases, their guts, their limitations – and people's sense of responsibility for the outputs of the models and how those outputs are used to make decisions about reality.

6. Measures to incorporate evaluation of opportunities for old data in process change management processes.
7. Root cause analysis process requirements for corrective action effectiveness evaluation and the provision of systems or tools that support the stewardship of corrective action effectiveness evaluations.
8. Measures to build persistence in pursuit of root cause(s) and to improve recognition of direct, contributing, and root causes.
9. Measures to nurture curiosity and a culture of productive questions.
10. Team member selections and team design to avoid groupthink.

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