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Case Study Pipeline Failure FMEA vs POFA for Proactive Failure Prevention Analysis

Let a Plant Wellness Way EAM System-of-Reliability halve your Annual Maintenance Costs

The request in the box below was received by email.

> I am contacting you to make you aware of Request, RFP# 68250, "**Breakthrough Technologies for Pipeline Leak Detection**."
>
> We invite proposals for **breakthrough technologies for pipeline leak prevention, detection, and remediation**. We have identified you as a party with the potential expertise to respond to this request.

Request RFP# 68250 was to find new and better ways to prevent leaks from gas and liquid carrying pipes, and/or detect and address leaks in overland pipelines before 10 barrels of content spilled. It was an opportune case to apply a fundamental tool in the Plant Wellness Way Methodology—Physics of Failure Analysis (POFA)—to see what solutions could be generated.

The standard way used world-wide to do conceptual failure analysis is by Failure Mode Effects Analysis (FMEA). In FMEA you list known failure modes that could occur to the item being investigated. A failure mode is what you observe upon failure of the item e.g., a damaged region, a discoloration, a hole, a score mark, etc. For each failure mode you then identify all the possible failure causes that lead to the failure mode.

In Physics-of-Failure Analysis you focus on the destruction of the materials-of-construction. You ask, "How is the material that makes up this item destroyed?" With POFA you first identify all stresses that fail the component material structure. Then you identify what scenarios during the item's life cycle produce those stresses. POFA uses the stresses that fail an item to discover how such stresses can arise. The end result of the POFA is to select proactive preventions of possible failure events so that excessive stresses do not arise and thus failure never happens.

To assist in identifying all stresses able to produce material failure we use Physics-of-Failure guidewords to trigger perceptive thoughts. Table 1 lists numerous causes of stress by situational and life cycle categories. From the list you select the mechanisms that can produce a sufficient stress that would to lead to a failure of the material in the component being investigated.

If you used FMEA you would start with a list of as many failure modes in overland pipeline walls as you could imagine. The list would include the following failure modes:

1. Leaking pipe
2. Leaking flange
3. Corroded pipe
4. Crack in pipe
5. Burst pipe
6. Cracked weld

You then identify as many failure causes of each mode as you can. Next you decide which causes are above ALARP risk levels[1]. Finally you address those causes with suitable strategy and actions. For the failure modes above you arrive at a FMEA list of causes including those noted below.

[1] ALARP: As Low As Reasonably Practicable

Failure Mode Effect Analysis List of Causes

1. Hole intentionally drilled through wall
2. Hole ground through wall
3. Hole flame cut through wall
4. Pipe blown-up with explosives
5. Flange face leak
6. Flange bolt looseness leak
7. Flange bolt fatigue leak
8. Gasket attack
9. Pipe fatigue stress
10. Weld cavity
11. Weld inclusion
12. Buckled wall
13. Corrosion outward through wall
14. Corrosion inward through wall
15. Crack in pipe material microstructure
16. Pressure burst wall
17. Internal wear through wall
18. External wear through wall
19. External impact on wall
20. Contents leak and explode
21. External fire weakens wall
22. Chemical attack internal on pipe wall
23. Chemical attack external on pipe wall

With the Physics of Failure method you work directly on stress mechanisms and not the failure modes. From the Physics of Failure Guidewords table you arrive at a list including those below.

Physics of Failure Analysis List of Causes

1. Compressive force overload
2. Tensile force overload
3. Shear force overload
4. Cyclic stress fatigue
5. Shock force overload
6. Punch hole in molecular structure
7. Melt molecular structure
8. Crack in molecular structure (dislocation)
9. Material missing from molecular structure
10. Material ripped from molecular structure
11. Wrong atoms in molecular structure
12. Chemical reaction
13. Crystal lattice attack
14. Metallurgy error
15. Formulation error
16. Process conditions error
17. Chemical composition error
18. Misalignment
19. Foreign inclusion
20. Thin cross section
21. Pressure
22. Physical deformation (bend, twist, squash)
23. Pressure hammer
24. Shrinkage
25. Expansion
26. Chemical reaction
27. Vibration
28. Oxidisation
29. Dissimilar materials
30. Weld penetration
31. Hygro-mechanical (moisture absorption)
32. Punch (Impact load on small area)
33. Hydraulic shock
34. Vibration shock
35. Abrasion (wear material away)
36. Hammer impact
37. Gouge
38. Impingement (jet of fluid)
39. Foreign inclusion in material
40. Detach-debond-delaminate
41. Acts-of-God/Acts-of-Nature
42. Fracture
43. Buckling
44. Yield
45. Creep
46. Material fatigue
47. Physical abuse
48. Vehicle impact
49. Soft material of construct (ease of wear)
50. Electrical discharge
51. Thermal high
52. Thermal low
53. Corrosion
54. Erosion
55. Electrostatic
56. Density gradient
57. Thermal gradient
58. Radiation
59. Inclusions in the process
60. Crystal lattice attack
61. Microbial/bacterial attack

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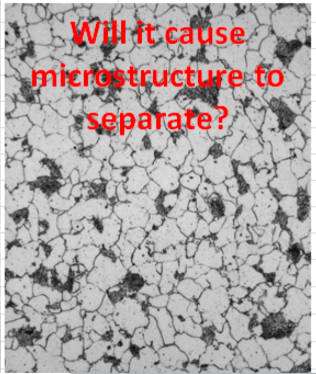
Physics of Failure Guidewords

Factors that cause Atomic or Microstructure Failure	Component Manufacturing Events	Component Operational Stress Events (Horizontal, Vertical, Axial)	Component Environmental Events / Conditions	Electronic / Electrical Effects	Component Life Cycle Situations
Compressive force overload	Metallurgy error	Pressure	Thermal high	Electrical discharge	Conception
Tensile force overload	Formulation error	Under-loaded	Thermal low	Electromagnetic	Feasibility
Shear force overload	Process conditions error	Interference fit tight	Microbial/bacterial attack	Electrostatic	Approval
Cyclic stress fatigue	Chemical composition error	Interference fit loose	Erosion	Metal migration	Final Design
Shock force overload	Interference fit tight	Insufficient load (looseness)	Corrosion (pitting, galvanic, crevice, etc)	Threshold Voltage Shift	Project Management
Punch hole in molecular structure	Interference fit loose	Physical deformation (bend, twist, squash)	Density gradient	Leakage current	Installation
Melt molecular structure	Misalignment	Pressure hammer	Thermal gradient	Power dissipation	Manufacture
Crack in molecular structure (dislocation)	Foreign inclusion	Shrinkage	Radiation	Stray electrical current	Assembly
Material missing from molecular structure	Thin cross section	Expansion	Diffusion	Ionisation	Operation
Material ripped from molecular structure	Weld penetration	Misalignment	Humidity	Tin Whiskers	Maintenance
Wrong atoms in molecular structure		Unbalance	Contaminant ingress	Electromigration	Overhaul / rebuild
Electromagnetic radiation		Punch (Impact load on small area)	Moisture ingress	Time Dependent Dielectric Breakdown	Transport
Chemical reaction		Hydraulic shock	Product ingress	Hot Carrier Injection	Storage
Crystal lattice attack		Vibration shock	Chemical reaction	Negative Bias Temperature Instability	Restitution
Depolymerisation		Abrasion (wear material away)	Vibration		
		Hammer impact	Rate of change of event		
		Gouge	Lubrication degradation		
		Impingement (jet of fluid)	Oxidisation		
		Foreign inclusion in material-of-construction	Dissimilar materials		
		Detach-debond-delaminate	Hygro-mechanical (moisture absorption)		
		Acts-of-God/Acts-of-Nature	Inclusions in contacting process		
		Fracture	Crystal lattice attack		
		Buckling	Elasticity degradation		
		Yield			
		Creep			
		Material fatigue			
		Physical abuse			
		Vehicle impact			
		Soft material of construction (ease of wear)			



PoF Strategy Development | PoF Guidewords | Risk Matrix

Table 1 List of Some Physics of Failure Guidewords

The guidewords trigger insightful thoughts related to each word or phrase. For example, 'Gouge' leads to thoughts of intentional damage to the pipe wall, accidental damage during manufacture or installation, damage to the pipe from rubbing on supports or against hard objects, etc.

Proposed Solutions

Request RFP# 68250 has two requirements that are totally different to each other. One is to identify how to prevent leaks happening. The other is to find a pipe leak before serious environmental damage results. The first requires a risk prevention strategy and the second requires a risk containment strategy. There two requirement lead to vastly different solutions.

Pipe Leak Prevention

To not have a pipe leak it is fundamental that the pipe wall is not breached by any cause, or combination of causes. The Plant Wellness Way methodology requires you to proactively prevent the cause of failure from arising. You prevent a failure starting by preventing its causes developing. Each item in the POFA list must be prevented from happening. To do that with high certainty requires that quality control and quality assurance be applied at every phase of the life cycle and supply chain—pipeline design, ingot manufacture, pipe manufacture, pipe fabrication, pipe installation, pipe operation, pipe maintenance. It requires a systematic failure prevention solution rigorously applied in all lifecycle phases and activities affecting the pipeline.

Such a solution is the Accuracy Controlled Enterprise 3T quality assurance methodology.

Pipe Leak Detection

The pipe stress causes in the POFA list can be categorised into lifecycle and supply chain issues. Because we are detecting a leak after the pipe failure has happened, we can dismiss any stresses due to metallurgy, pipe manufacturing, pipe installation and poor process operation of the fluid in the pipe. This would not be so if you wanted to prevent pipe wall failure. Proper pipe manufacture, correct low-stress pipeline fabrication and installation, controlled process conditions and process chemical composition are all critical in preventing pipe failure. What remains of the list after dismissing metallurgical, manufacture, installation and operation error causes are:

1. Punch hole in molecular structure
2. Melt molecular structure
3. Material ripped from molecular structure
4. Physical deformation (bend, twist, squash)
5. Oxidisation
6. Punch (Impact load on small area)
7. Gouge
8. Chemical reaction
9. Impingement (jet of fluid)
10. Acts-of-God/Acts-of-Nature
11. Physical abuse
12. Vehicle impact
13. Electrical discharge
14. Corrosion
15. Erosion
16. Electrostatic
17. Crystal lattice attack
18. Microbial/bacterial attack

These causes can occur anywhere along the pipeline. Some causes are outside events adversely damaging pipe wall integrity. The remainder of events affect the pipe wall from the inside. Some events are short lived, such as direct impact, gouging and Acts of God. Others occur over great lengths of time, such as erosion, material attack and corrosion. The time when the pipe wall is finally breached will never be known. But the effect of the breach will be seen as a leak from the pipe. At that stage all that is left for you to do is limit the consequential damage by quickly finding the leak's location while, hopefully, containing the leak until it is found.

Leak Detection and Containment Suggestion

Our proposition to meet the request of pipe leak detection before ten barrels of contents escape is to apply a spray-on plastic membrane that expands like a balloon when a leak occurs. The entire pipeline and flanges are encapsulated in the flexible sheath. Once the membrane swells and collects the fluid, you will see a lump hanging from the pipe. This allows use of visual methods to detect the containment pocket. We suggest that infrared cameras be used to detect pipe temperature differences from swellings.

Explanation of Suggestion

Fluid collects under your skin when your body is hit hard enough to cause swelling. The skin does not rupture but instead fluid bulges the skin into a lump. That behaviour is what is intended to happen by using a sprayed plastic membrane. A spray-on plastic sheath with high stretch properties would firmly hug the pipe until a leak forced it to expand off the pipe. The lifted membrane would be detectable by its bulge.

The plastic spray-on membrane would need to have excellent expansion properties so it swelled into a balloon and did not burst. The membrane must pull tight onto the pipe yet always be able to lift and form a containment pocket at any time and place. It cannot physically bond onto the pipe since it must peel off the pipe to form a growing cocoon of contained fluid as pressure and fluid is released from the pipe. As the cocoon grows the sheath should peel back without lifting the rest of the sheath from the pipe. It will probably require the pipe to be roughened by grit blasting to provide attachment of the plastic to the pipe so as to permit peel-back without lifting the entire sheath. This behaviour has to be tested in laboratory trials, because, depending on the properties of the plastic, it also may not need pipe surface preparation.

Delamination by a small amount of fluid of insufficient quantity to create a large visible bludge could be detected by thermal imaging. Temperature differences would arise from fluid collected in containment pockets. For rapid leak detection we suggest daily fly-passes of the pipeline with manned or drone aircraft carrying thermal imaging cameras.

On insulated pipes the plastic membrane is first put over the pipe and then all is covered with insulation. Once the membrane swells it will lift the insulation.

Benefits of the Pipe Membrane Proposal

1. For weeping liquid leaks the plastic membrane contains the discharge and collects the loss. Heavier leaks of liquids should also be contained by an expanding pocket. For slow gas line leaks the sleeve should withstand the leakage pressure, whereas tremendous gas pressure venting is likely to burst the membrane. The pressure limits and ballooning behaviours of the sheath on liquids and gasses need to be trialled and tested.

2. The plastic membrane may even replace the pipe paint coating and save the cost of painting the pipe. There may be no extra costs for pipe plastic membrane coating compared to covering a pipe with conventional painted coatings.

3. Plastic spraying technology is readily available, as are the plastics to be sprayed.

4. Leaks of flammable liquids and gasses will be contained by the membrane and not be exposed to ignition sources around the pipe. Within the bludge the gas and vapour concentrations will so high that a flame cannot be sustained.

5. For new pipes the membrane can be installed during the pipe making process. A method like that used to put protective sheaths on underground gas pipes maybe more cost effective than spraying.

6. Maintenance and repair of the membrane is expected to only require cleaning the pipe and recoating over the areas of damage. It would be necessary that the new membrane physically bonds to the old membrane that remains.

Draw-Backs of the Membrane Proposal

1. Once a pipe is under a membrane sheath the pipe wall, welds, flanges and flange bolts cannot be seen. This demands high quality control in pipe manufacture and pipe installation so causes of pipe failure and flange leakage are not introduced and hidden under the sleeve. Once pipes are unobservable you return to the need for a lifecycle and supply chain quality assurance system to prevent the cause of problems happening in the first place. As previously advised, for this we offer our Accuracy Controlled Enterprise 3T quality assurance methodology.

2. The expansion and ballooning properties of current sprayed plastics need to be investigated. It may be necessary to develop new plastic formulations with the required properties of ballooning and containment.

3. Where the membrane is to be the pipe coating, the thickness of plastic to protect the pipe from corrosion during its years of service is unknown. The coating will need to be replaced if age or pipeline usage leads to degradation of its properties.

4. Where gasses collect under the membrane they will balloon the sleeve. If the chamber contains explosive gasses and the membrane leaks heavily or ruptures a gas cloud maybe rapidly ejected.

5. The membrane is unlikely to contain pipe bursts or high pressure jet discharges.

6. A plastic material would burn during a fire.

My best regards to you,

Mike Sondalini
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