The Challenges of Troubleshooting

David E. Mertz, P. E., Fermi Research Alliance

Introduction

Why isn't this *The Challenges of **Electrical** Troubleshooting?*

- So much of the equipment and systems that electrical workers may be called on to troubleshoot contain or interact with other sources of hazardous energy.
  - Compressed Air
  - Mechanical motion
  - Hydraulic Systems
  - Hot, cold, corrosive or toxic fluids or materials

- Even "purely electrical" equipment may have non-electrical hazards.
  - Compressed springs driving mechanical actions in power circuit breakers
  - Sharp edges on electrical enclosures
  - Work environment with slip-trip-fall, pinch points, struck-by risks or poor weather conditions

The Troubleshooting Process

LOTO May not Save You this Time

- Lockout / Tagout procedures assume the subject equipment is in a normal operating state, or something close to it.
- Pretty much by definition equipment that needs troubleshooting is not in a normal operating state, and it likely remains to be determined how far away from that normal operating state it is.
- That non-normal state may relocate or add hazards where a worker might not expect to find them.
- Some troubleshooting may be infeasible with the equipment de-energized.

* Apologies to Derek Lowe and his original blog post *Sand Won't Save You this Time.*

Thomas Jefferson National Accelerator Facility
Friday 26 April 2019, 15:00

- Subject Matter Expert (SME) began troubleshooting a Radio Frequency Separator that had been left in an energized, partially closed condition by a technician who had been previously been attempting to fix it.

- SME contacted a high voltage source as he was removing a cover, burning a hand and a wrist and causing “severe tingling” in both arms.

- SME exited building and got the attention of an employee driving past who help him get prompt medical attention.

Residential Basement, Cleveland, Ohio, the late 1970s

- A teenager running a consumer electronics repair business out of his parents' basement was troubleshooting a console color TV.
- To discharge the CRT, he connected a jumper between the flyback cage and a long-shafted screwdriver and shoved the screwdriver tip under the CRT anode clip cover and received a shock. More "severe tingling."
- A household member had used the screwdriver as a chisel and driven the shaft through end of the handle.
- Electricity takes every available path, not just the least – resistant one

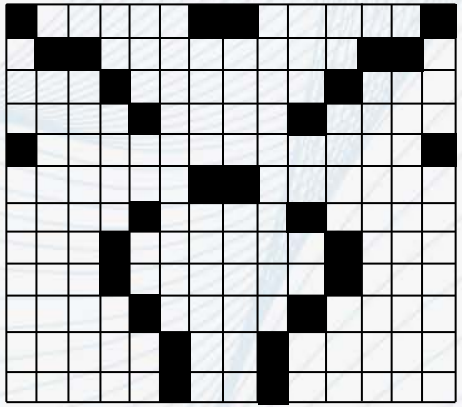
Image from Wikimedia Commons, licensed under Creative Commons Attribution-Share Alike 3.0 Generic by Blue tooth7. Link: https://w.wiki/8iho

Old Yeller syndrome

- Equipment and systems in their normal state can become as familiar to workers as a family pet.
- Abnormal conditions can add or relocate hazards in equipment and systems much in the way that rabies can transform the behavior of a previously docile animal.
- Approaching malfunctioning equipment should be done with an expectation that unexpected hazards are present.
  - Exterior components may be energized.
  - Controls such as emergency stops and other interlocks may not function as intended or expected.

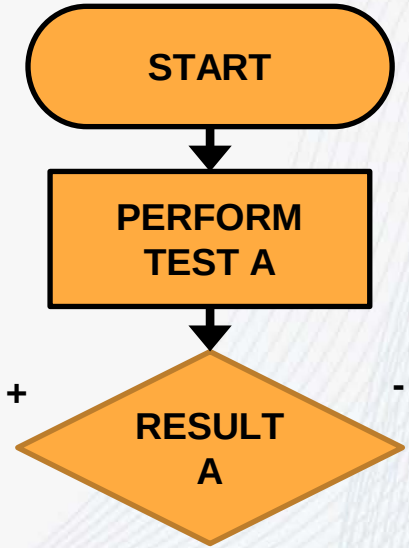
Detective work and puzzle-solving

- Troubleshooting work should begin like a crime investigation
  - Control the “scene”
    - Observe the state of the equipment
    - Gather mangled or out-of-spec products
  - Interview “witnesses”
    - Ask what happened when and in what sequence
    - Were there any abnormal conditions, even those not apparently associated with the equipment of interest
- This can often narrow down the possible causes.



Detective work and puzzle-solving

- Now for the puzzle-solving challenges
  - What test should be done first?
  - What do the first test results mean?
  - Did that first test identify the problem or are more tests needed?
  - What test should be done second?
  - What do the second test results mean?
  - Did that second test identify the problem or are more tests needed?
  - Repeat, repeat, repeat…



Detective work and puzzle-solving

- More steps
  - What test should be done first?
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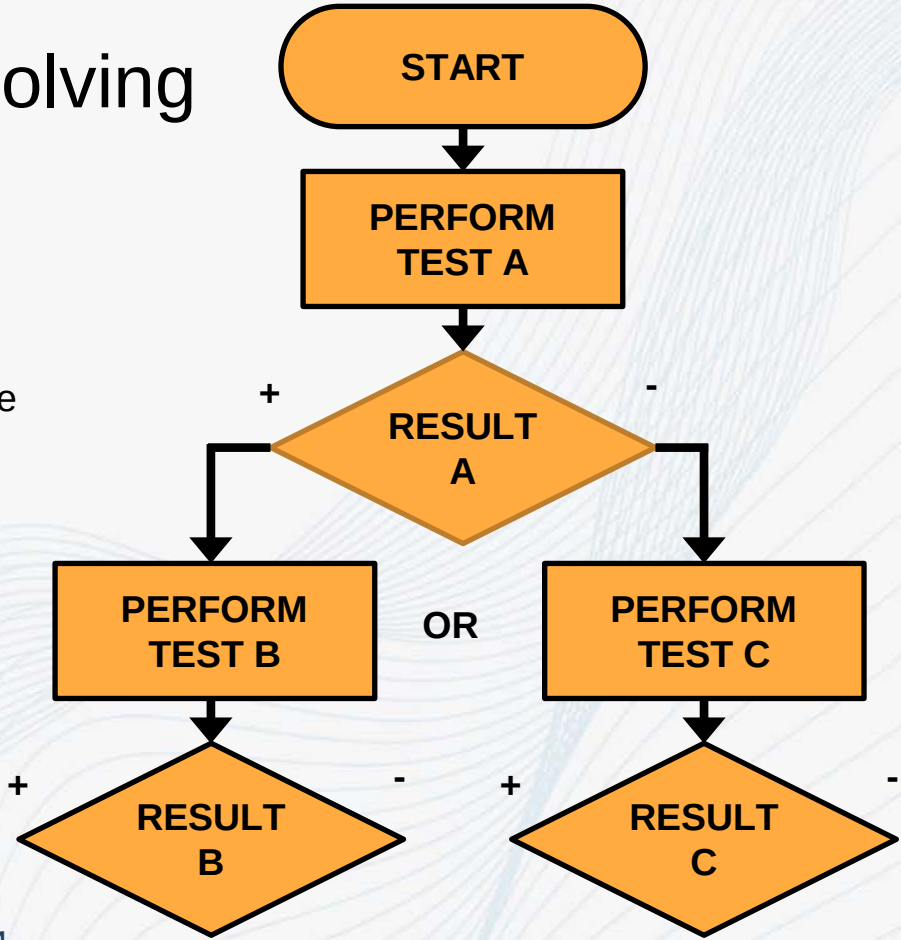
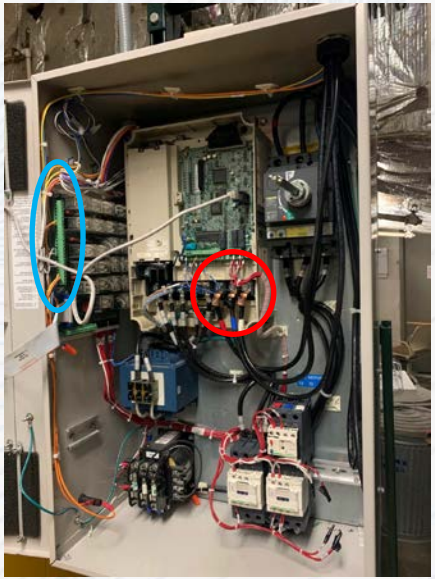
- **Wait a minute…**



Argonne National Laboratory, 28 September 2023

- Four workers were troubleshooting a communication failure between a Building Automation System (BAS) cabinet and a Variable Frequency Drive (VFD)
- Electrical Engineer (EE) used VFD front panel controls to simulate conditions the BAS should recognize, but the BAS did not recognize the signals.
- EE opened VFD enclosure to access the low voltage signal terminal (blue oval) to measure signals and check low voltage wiring and inadvertently exposed power terminals (red circle).
- Safety personnel observed VFD was not in LOTO and had electrical hazard warning label on its door.



Dog on a Scent

- It is incredibly easy for a troubleshooter to focus on hunting down the recalcitrant component(s) to the exclusion of just about everything else
  - Time
  - Meals
  - Coffee
  - **Job hazards**

Detective work and puzzle-solving

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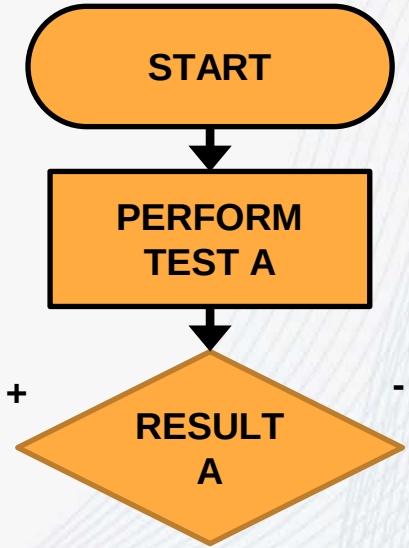
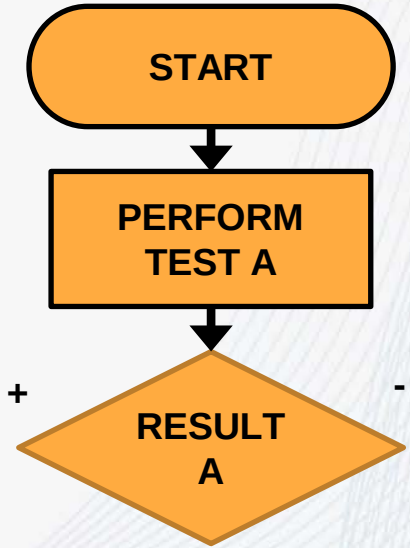


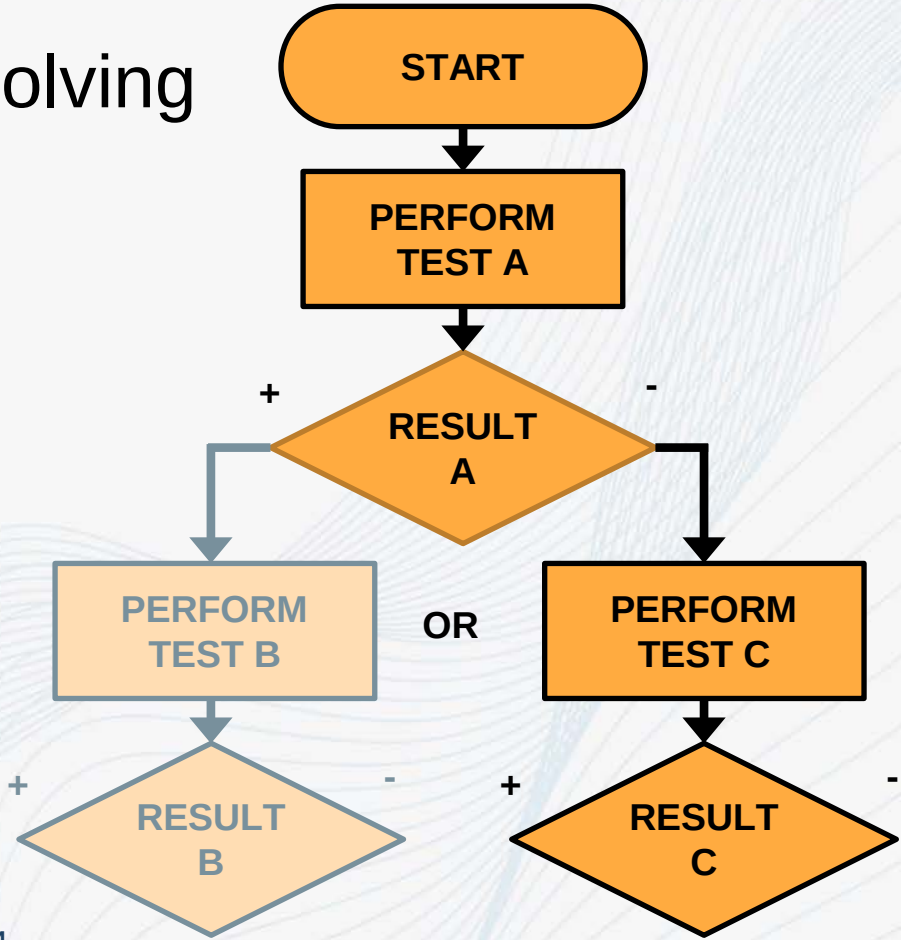
Detective work and puzzle-solving



- Puzzle-solving when troubleshooting
  - What test should be done first?
    - **What are the hazards of performing this test?**
    - **Is there a safer way to do this test?**
    - **Can this test be done under LOTO?**
    - **Do we need other hazard mitigations?**
    - **Prepare and review JHA**
  - Perform the first test
  - What do the first test results mean?
  - Did that first test identify the problem or are more tests needed?
- **Pause work**

Detective work and puzzle-solving

- Now do that again
  - What test should be done second?
    - **What are the hazards of performing this test?**
    - **Is there a safer way to do this test?**
    - **Can this test be done under LOTO?**
    - **Do we need other hazard mitigations?**
    - **Prepare and review JHA**
  - What do the second test results mean?
  - Perform the second test
  - Did that second test identify the problem or are more tests needed?
- **Pause work**



So what did that change do?

- Hazards and mitigations are now identified at every troubleshooting step.
- The troubleshooting process just got a lot safer.
- The troubleshooting process sure didn’t get quicker (unless you avoided hurting somebody).
- Who cares about time anyway?

Metal machining job shop, Northeast Ohio, 1986

- An early-career maintenance technician troubleshot a stamping press with a “hot job” had significant misoperation issues.
- Once the problem was located to a row of limit switches on the main crank, safety locks were placed on the control cabinet disconnect, compressed air block and bleed valves, and steel blocks that propped the die set open.
- By shift change only calibrating the limit switches and replacing covers and guards remained to be done.
- The afternoon shift foreman removed the safety locks and test cycled the press.
- A 3/8” die set guide pin pierced the maintenance technician’s right foot between the 3rd and 4th metatarsals.
- Returning the press to service was delayed by approximately 12 hours.

What makes troubleshooting particularly hazardous?

- Multiple physical hazards and sources of hazardous energy
- One or more significant unknowns
- A knowledge-based activity as defined by Human Performance
- Time pressure to return equipment or systems to operation
- Less than adequate communications
- Not a field with an established course of study or apprenticeship program

Expediting Troubleshooting

What can be done to reduce troubleshooting risk?

- Ensuring that workers have the skills to perform the troubleshooting
- Provide troubleshooters with facts and data about the derangement
- Improve work planning and control
- Relieve time pressure on troubleshooters

Why is this so important for electrical workers?

- Electrical systems provide much of the energy needed to operate equipment
- Electronic controls centralize information on status and operation onto a computer screen for even for physically, even geographically, large systems
- Those same control interfaces may be how operations personnel become aware that there's a problem, so the controls may be perceived as the source of the problem until the electrical workers prove otherwise.
- Access to the inner workings of control systems can allow electrical workers to bypass interlocks and other protections, with potential for additional harm.

Methods to reduce troubleshooting risk

- Careful work planning and control
- FMEA – based troubleshooting
- Downtime – resistant design
- Alarms, alarm logs, and time stamping
- Thorough process monitoring
- Thorough program documentation

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Careful work planning and control

- Troubleshooting work demands work planning at least as much as any other type of work.
  - Hazards are likely to be different during different troubleshooting steps.
  - Each step needs to be reviewed for changes in hazards.
    - The next step may have additional hazards that the previous step did not.
    - There may have been hazards present in the previous step because that step was infeasible without them that can now be removed before performing the next step.
  - Defining and respecting the boundary on the scope of work for each troubleshooting step is critical – knowing when to pause.

Careful work planning and control

- Time pressure will undermine effective work planning while troubleshooting
  - Troubleshooters need to resist time pressure to shortchange work planning.
  - Safety professionals may need to stand between the troubleshooters and other personnel that may be expressing the time pressure.
  - Safety professionals may also need to encourage, and if necessary enforce, work planning requirements and scope of work boundaries with troubleshooters.

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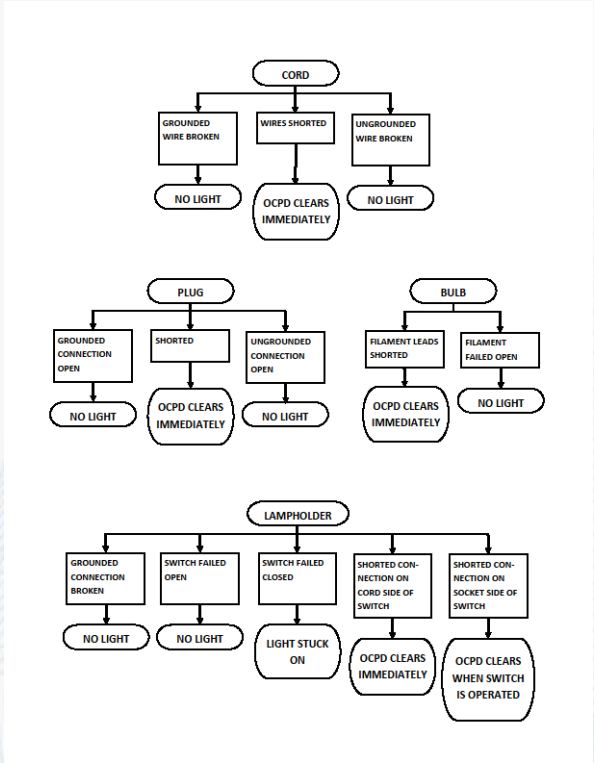
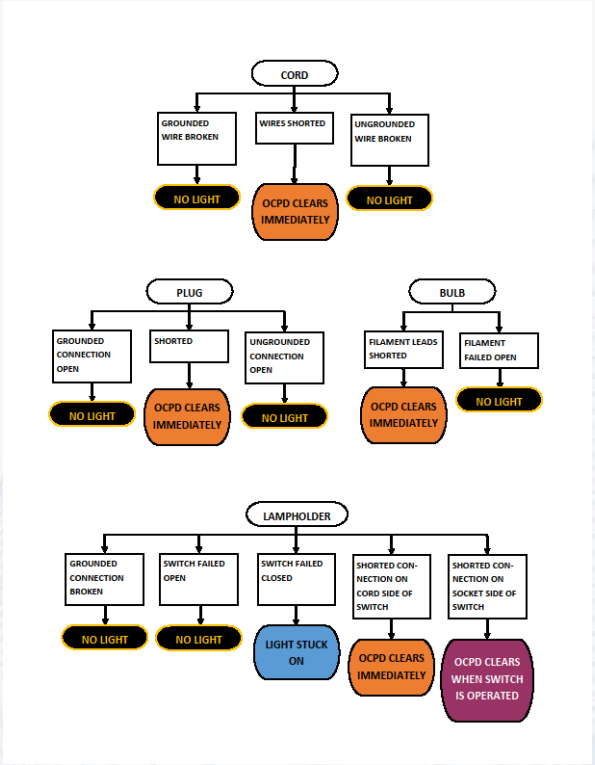
FMEA-based troubleshooting

- Starts with a very simple FMEA
- MTBFs and other data and features can enhance the results but are not necessary.
- If a FMEA is already prepared for other purposes, leverage it!



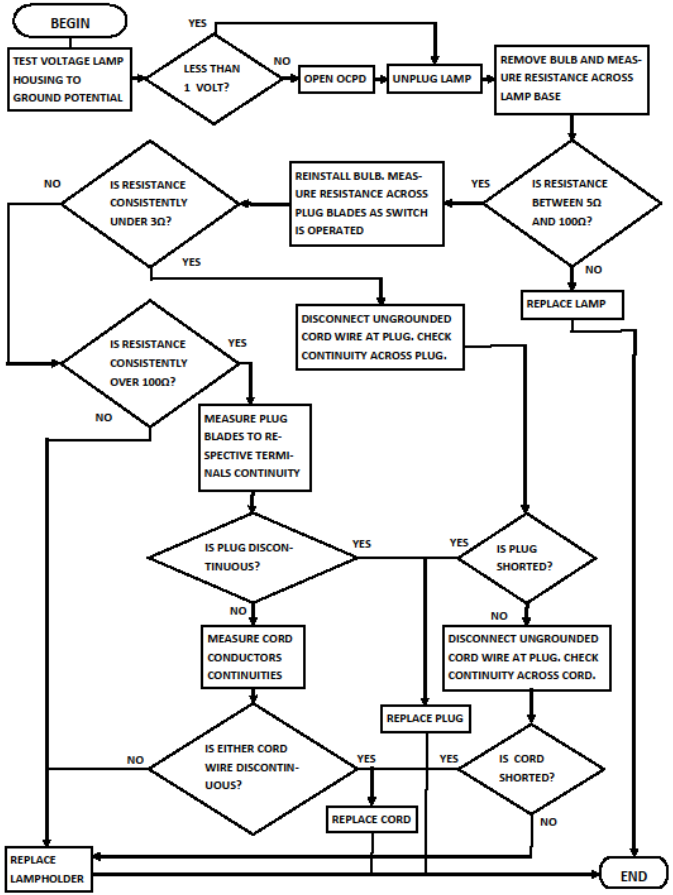
FMEA-based troubleshooting

- FMEAs start from the components and figure out the symptoms.
- FMEA-based troubleshooting starts from the symptoms and figures out the responsible components.



The Inverted FMEA

- Consolidates identical symptoms.



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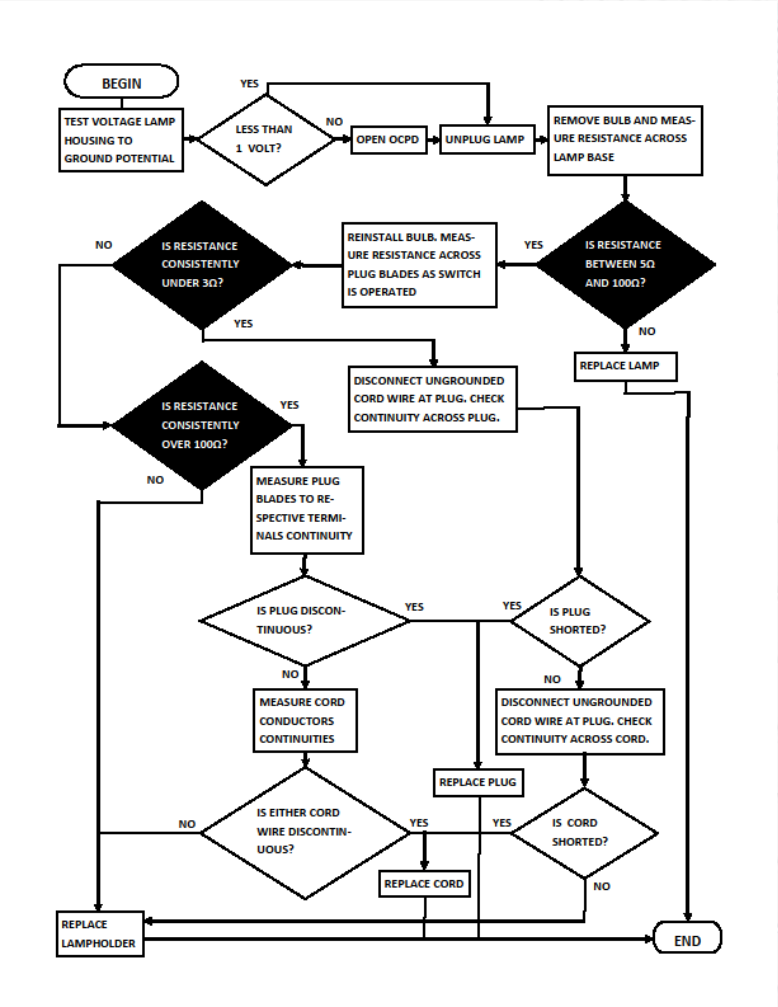

The Inverted FMEA

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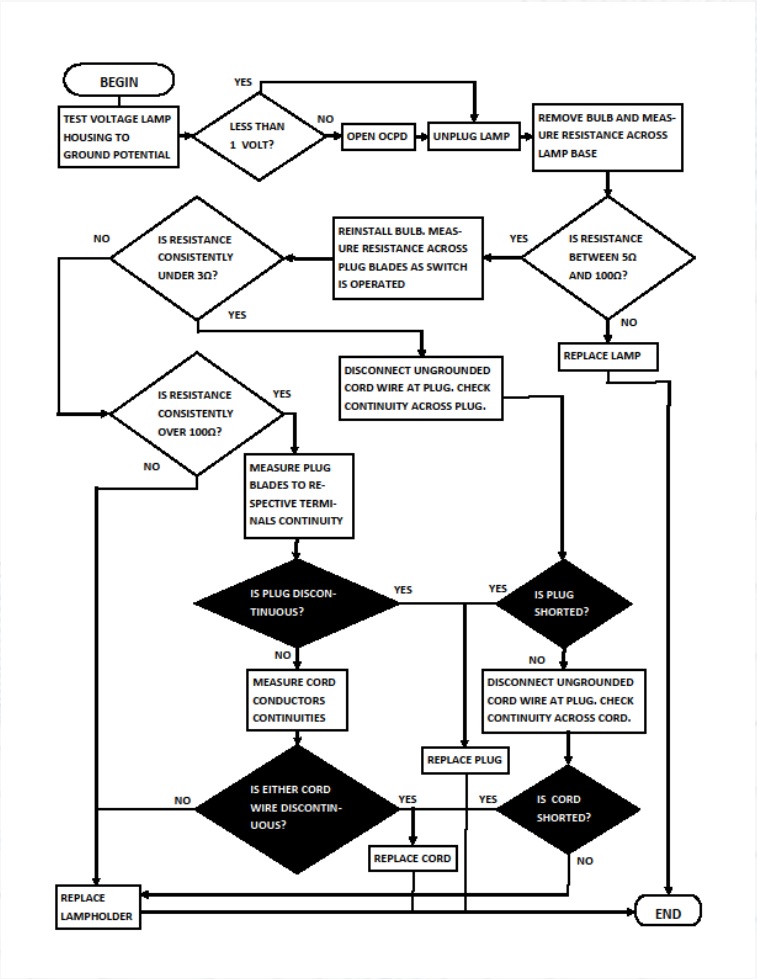
- First tests distinguish between symptoms.
- Following steps distinguish between components that may have identical symptoms for their failures.



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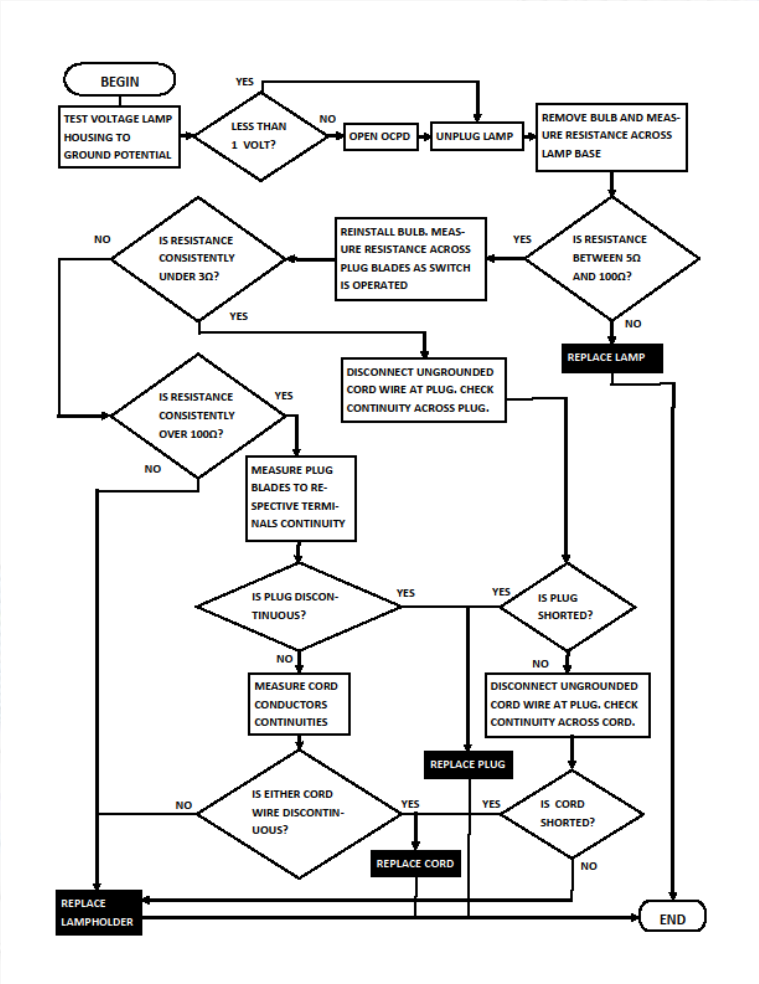
- Following steps distinguish between components that may have identical symptoms for their failures.
- Final steps prescribe repairs.



Benefits of the Inverted FMEA

- From a Human Performance perspective*
- Three performance modes
  - Knowledge-based. Error rate 10% to 50%
  - Rule-based. Error rate 0.1%
  - Skill-based. Error rate 0.01%

* DOE-HDBK-1028-2009, Human Performance Improvement Handbook, Volume 1: Concepts and Principles

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  - Skill-based. Error rate 0.01% ← The equipment has some serious, repetitious problems.

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Benefits of the Inverted FMEA

The Inverted FMEA ought to be able to take us from here to there.

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Other benefits of the Inverted FMEA

- Relieves the troubleshooter of much of the mental burden
- Predetermined steps permit procedures and JHAs to be developed in advance of the need for troubleshooting

Costs of the Inverted FMEA

- Significant up-front effort and investment
- Some of the procedures and JHAs may never be used
- Ongoing investment to review and update the Inverted FMEA

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} Efficiency, Accuracy and Safety

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What if there isn’t an Inverted FMEA?*

- The troubleshooter **with** an Inverted FMEA has two main tasks:
  - Safely follow the procedures in the Inverted FMEA
  - Perform the repair

- The troubleshooter **without** an Inverted FMEA has five main tasks:
  - **Figure out each step in the troubleshooting process**
  - **Develop the JHA for each step**
  - Safely follow the procedures just developed for each step **AND PAUSE**
  - **Analyze the results of each step**
  - [repeat as required]
  - Perform the repair

*or something like it

Benefits without an Inverted FMEA

- No Significant up-front effort and investment

Costs without an Inverted FMEA

- The troubleshooter effectively creates the Inverted FMEA step by step – but is the result of that effort remembered (documented) or forgotten?
- A responsible troubleshooting process becomes more cumbersome
- Even a responsible troubleshooting process becomes far more error-likely
- Organizational expectations may encourage shortcuts

Methods to reduce troubleshooting risk

- Careful work planning and control
- FMEA – based troubleshooting
- **Downtime – resistant design**
- Alarms, alarm logs, and time stamping
- Thorough process monitoring
- Thorough program documentation

Downtime Resistant Design

- Select equipment robust. enough for its service conditions
- Design in redundancy where criticality of continuous service or expected failure rate recommend.
- Readily swappable spare equipment
  - Hot or not

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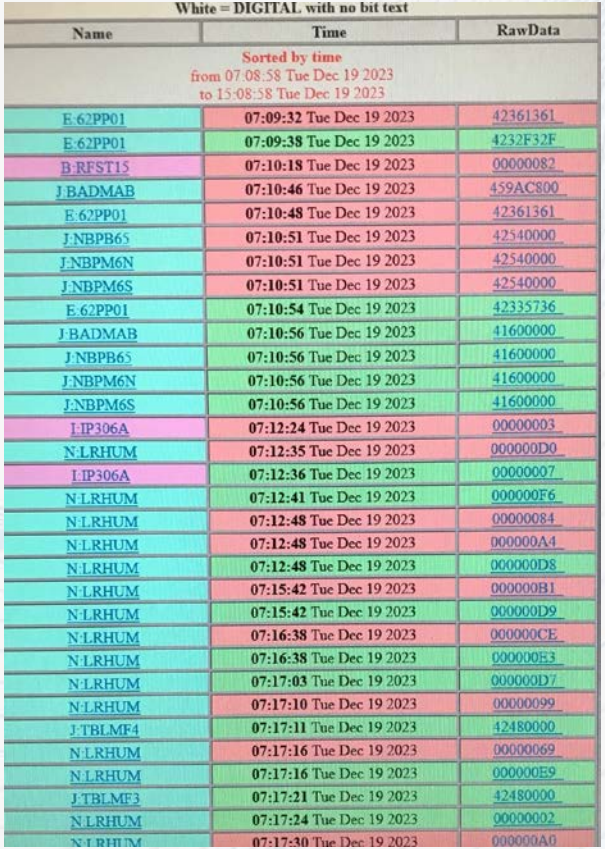
If you've got a control system…

- Alarm and event logs are a troubleshooter's gold mine
  - Operators and troubleshooters likely have different expectations of control system alarms.
  - Not all troubleshooting alarms may need to be displayed to operators. What is valuable to a troubleshooter may be a nuisance to the operator. Would separate alarm logs for Operations and Maintenance be of value?
  - Alarm and event logs are vital to the troubleshooter's detective work to document sequences of events.
  - Like the Inverted FMEA, thorough alarming and logging implementation requires up-front investment during control system development.



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from 07:08:58 Tue Dec 19 2023
to 15:08:58 Tue Dec 19 2023

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J:BADMAB	07:10:46 Tue Dec 19 2023	459AC800
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J:NBPB65	07:10:51 Tue Dec 19 2023	42540000
J:NBPM6N	07:10:51 Tue Dec 19 2023	42540000
J:NBPM6S	07:10:51 Tue Dec 19 2023	42540000
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J:NBPM6S	07:10:56 Tue Dec 19 2023	41600000
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N:LRHUM	07:12:35 Tue Dec 19 2023	000000D0
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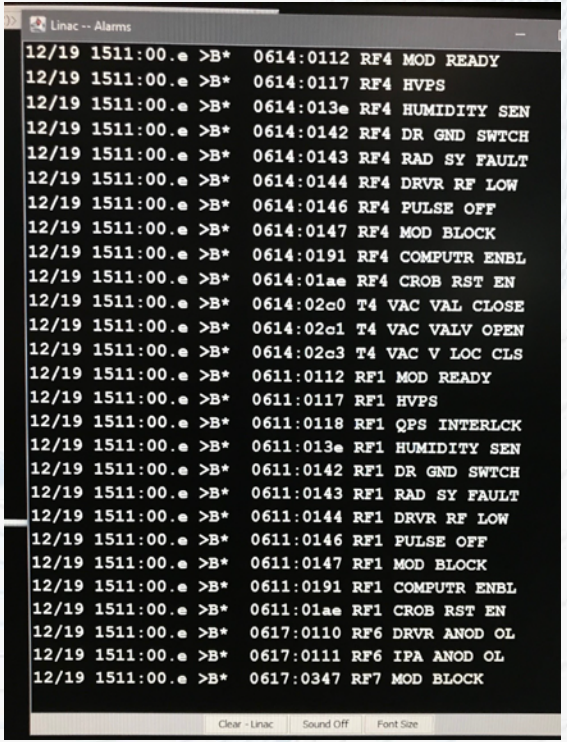
If you’ve got a control system…

- Alarm and event logs are only as good as the information the control system gets from the equipment or system.
  - What isn’t monitored can’t trigger an alarm.
  - Does your control system control a component? Then monitor it!
  - Rich monitoring generates lots of evidence for the troubleshooter’s detective work.



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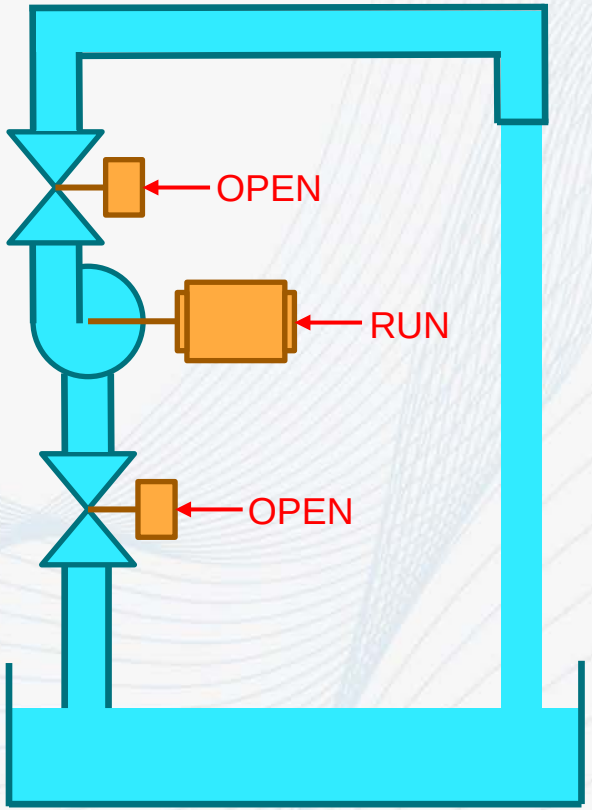

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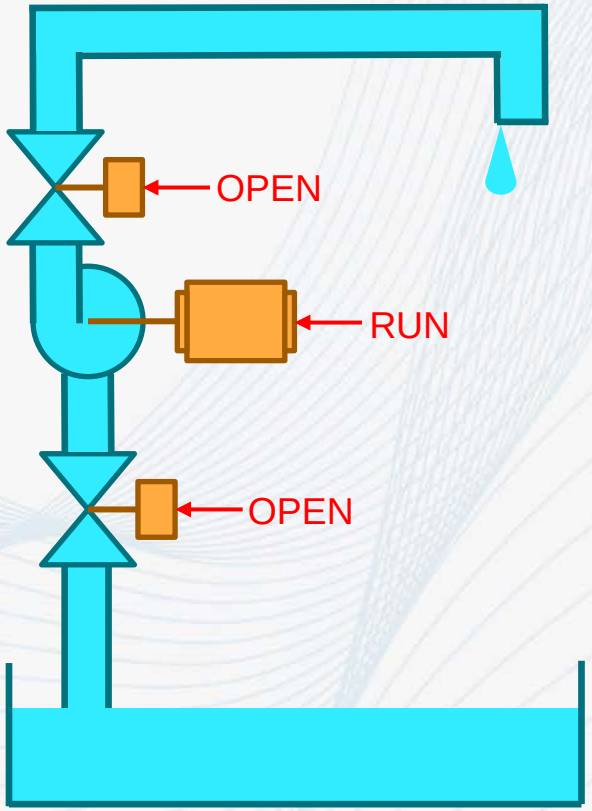

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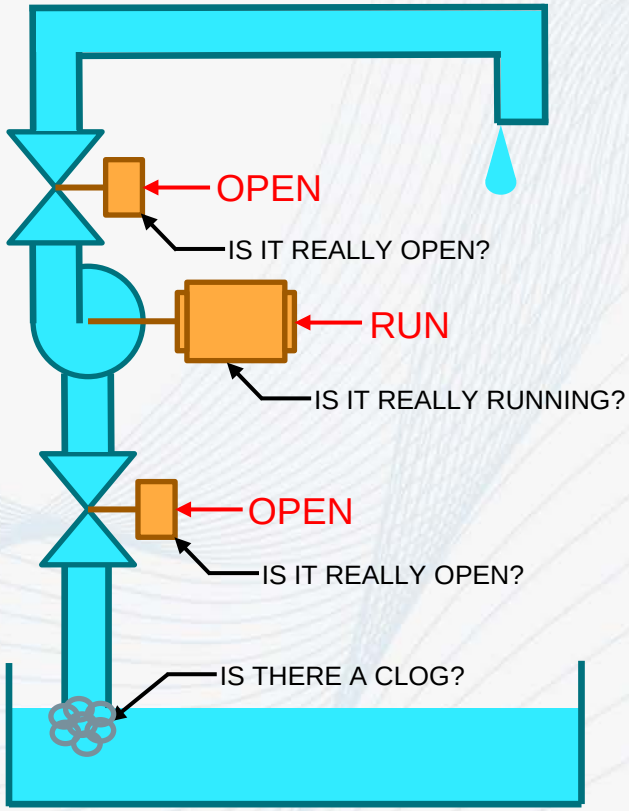

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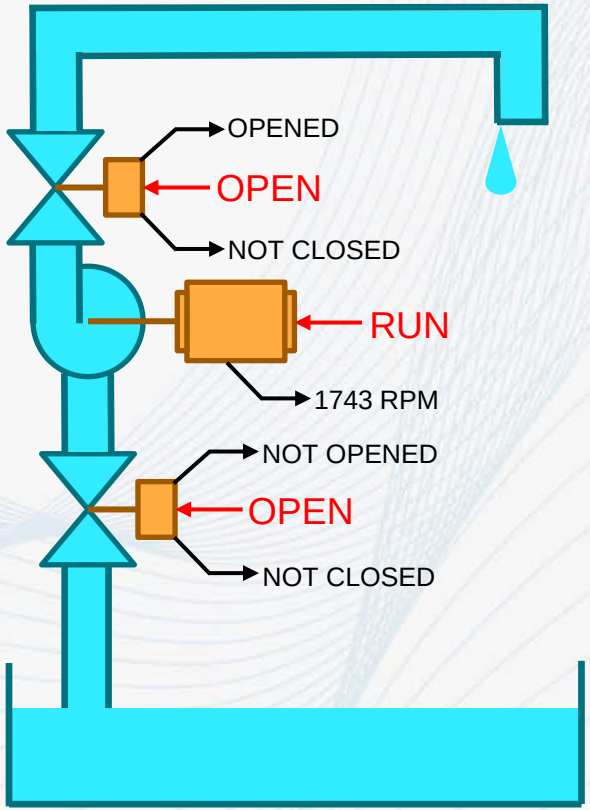

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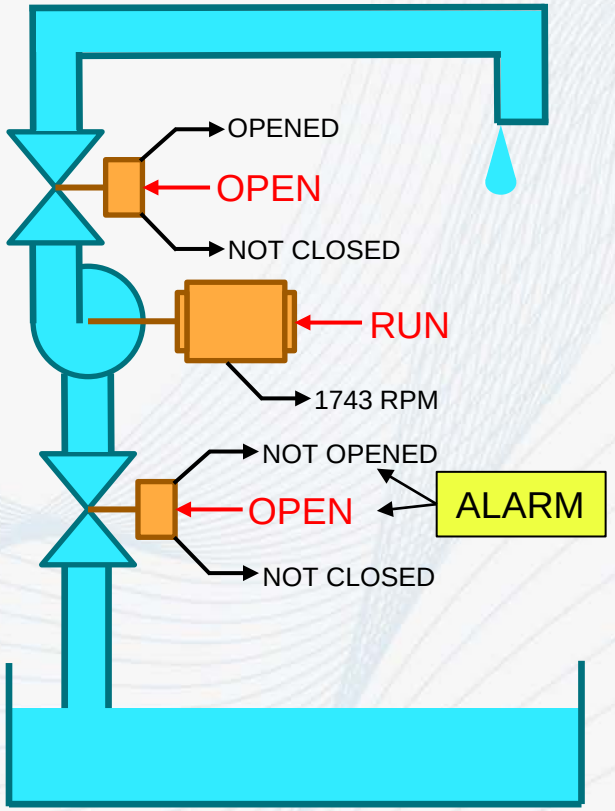

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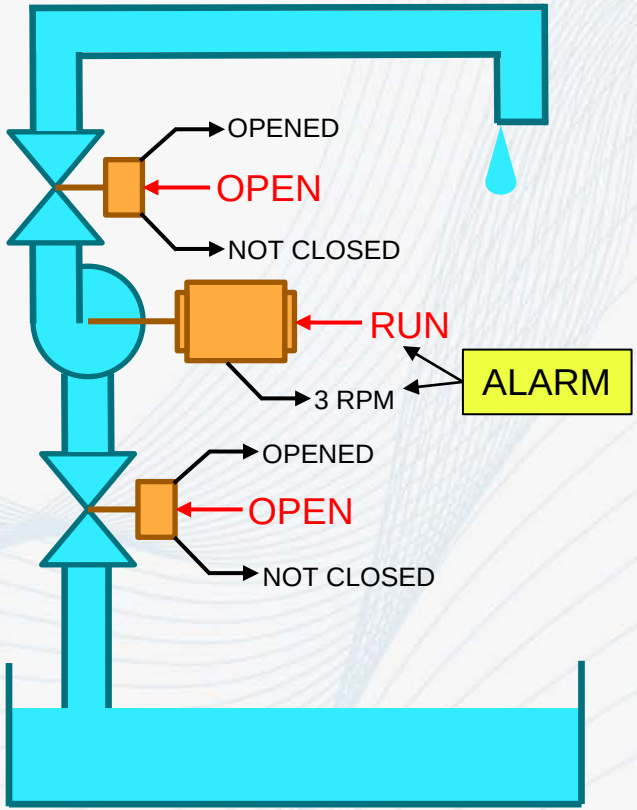

If you've got a control system…

- Alarm and event logs are only as good as the information the control system gets from the equipment or system.
  - Does your control system control a component? Then monitor it!
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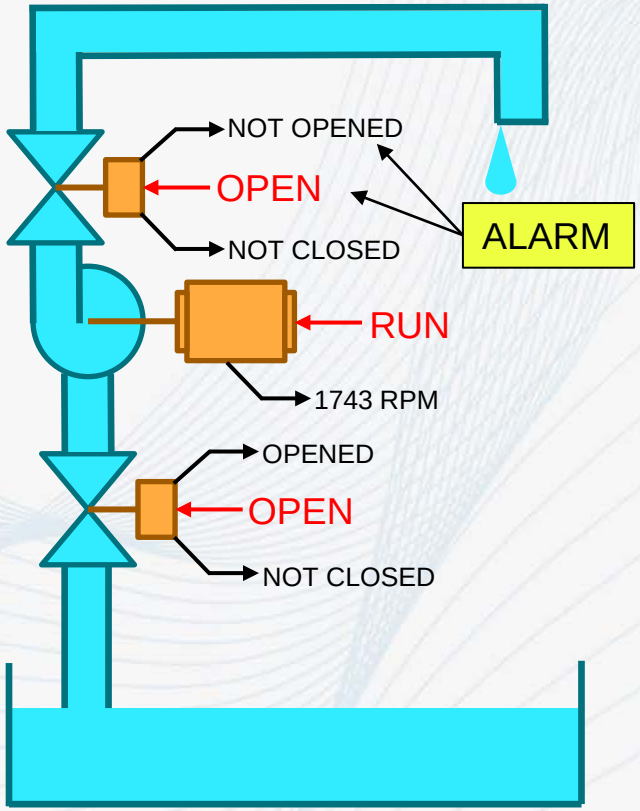

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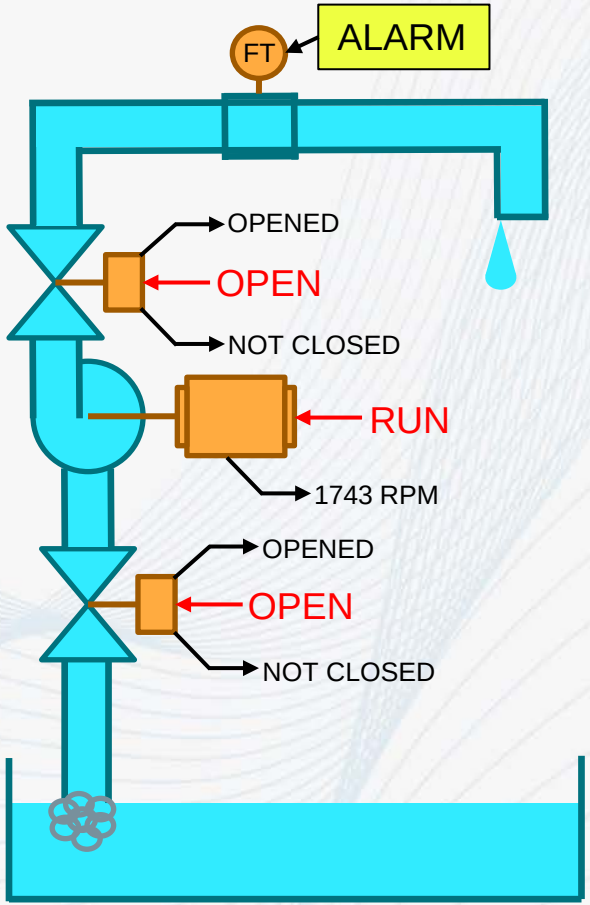

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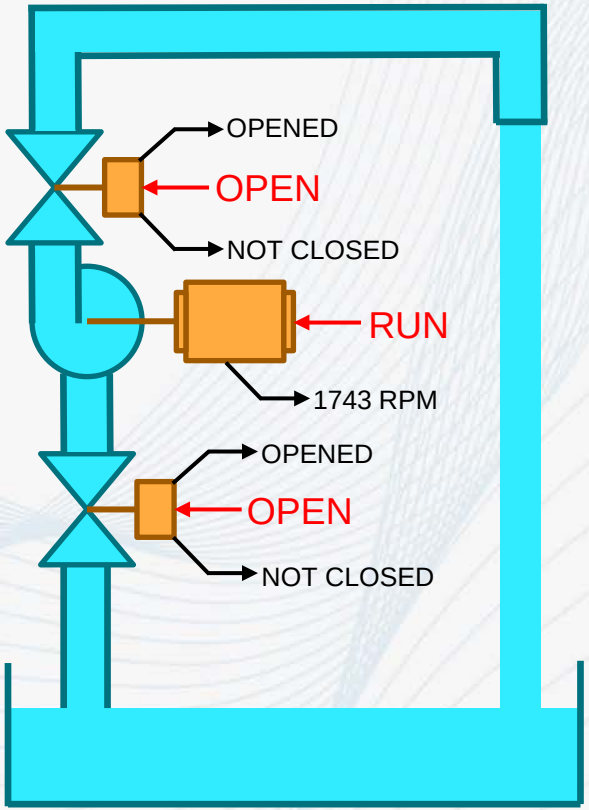

Methods to reduce troubleshooting risk

- Careful work planning and control
- FMEA – based troubleshooting
- Downtime – resistant design
- Alarms, alarm logs, and time stamping
- Thorough process monitoring
- **Thorough program documentation**

Program documentation

- If a troubleshooting effort leads the troubleshooter into a control system's program…
  - Troubleshooting in an undocumented program is like navigating a city without any street signage. And without a GPS. Or a PPS. Or even a local riding shotgun.
  - To paraphrase Donald Knuth, "Do not write your code to be read by a machine. Write it like a piece of literature to be read by people. You will do both yourself and those who may come after you a huge favor when the program has to be maintained, modified, or troubleshot."
  - It's perfectly fine to use mathematical magic, subtle subroutines, and arcane apps to implement your controls. Just please explain them. Clearly.

Future work

Troubleshooting education and certification

- There are several reasons why troubleshooting seems to be a “black art”
  - A individual’s troubleshooting prowess may be restricted to certain processes, types of machinery, even specific manufacturers’ products.
  - Even more so than lighting design, there is no course of study, formal apprenticeship, degrees, or other certifications.
  - Those who are good at troubleshooting may perceive that their job security is enhanced if they are the only ones possessing the resources or knowledge to do it.
  - Employers may not offer recognition or compensation specifically acknowledging good troubleshooting skills.

Conclusions & Questions

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- Troubleshooting is often a risk-prone, error-prone activity.
- Appropriate work planning can dramatically reduce the likelihood of safety hazards and erroneous decisions, arguably by a couple orders of magnitude.
  - Electrical and general safety professionals have a role to play in ensuring adequate work planning.
- The Inverted FMEA process is a way to prepare this work plan in advance.
- Control systems offer opportunities to expedite a troubleshooter's work.
- Formalization and codification of troubleshooting education and qualification should be considered.

Thank you

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