INL/MIS-23-72365-Revision-0

Natural Language Processing-Enhanced Nuclear Industry Operating Experience Data Analysis: Causal Learning and Inference

May 2023

Sai Zhang

Changing the World's Energy Future

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Natural Language Processing-Enhanced Nuclear Industry Operating Experience Data Analysis: Causal Learning and Inference

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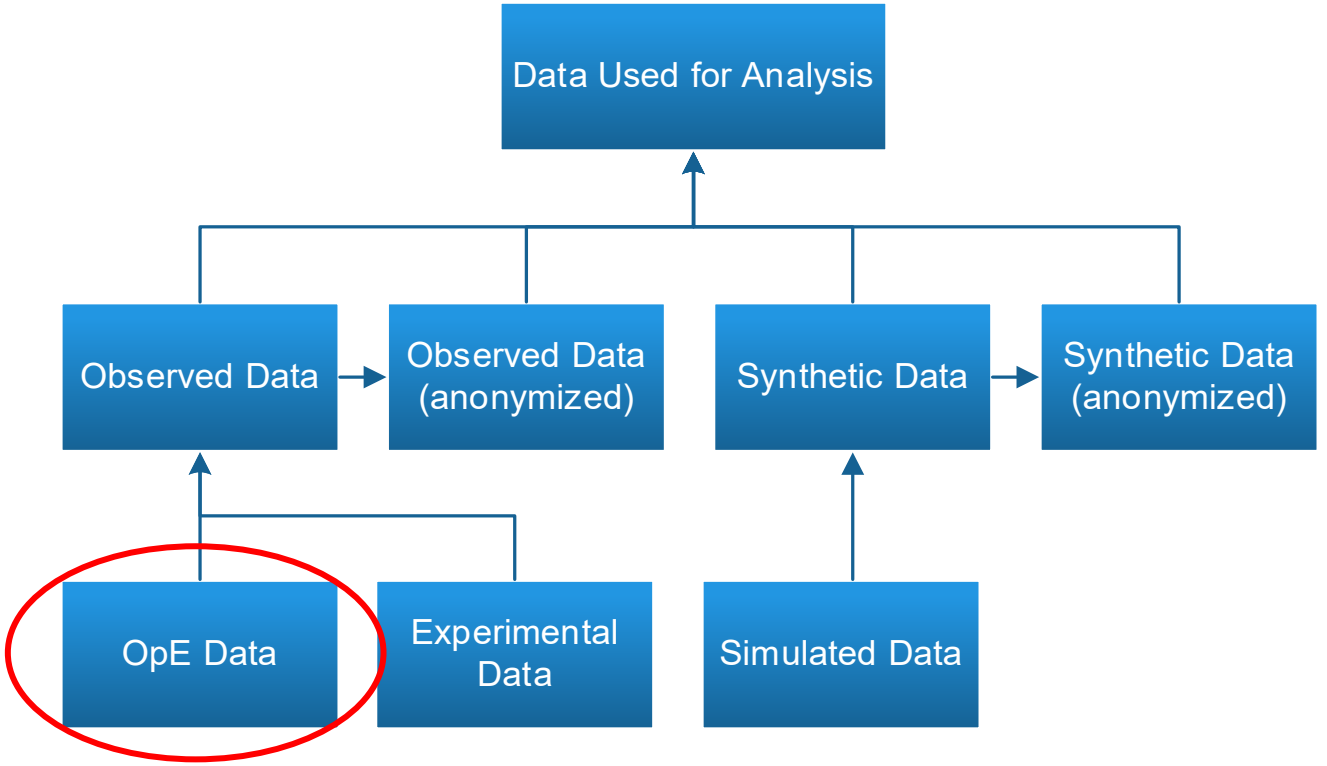
Idaho National Laboratory

Background

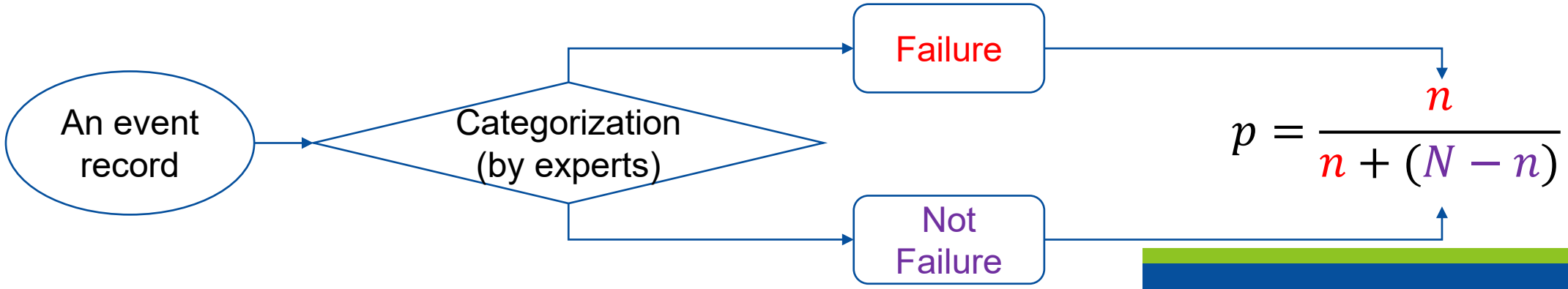
- **Nuclear power plant operating experience (OpE) data**
  - The data observed and harvested as nuclear power plants operate
  - Can be categorized using multiple characteristics including:
    - Data (or file) format
      - e.g., free-text data
    - Data structure
    - Data velocity
    - Data accessibility
    - Relevancy to probabilistic risk assessment (PRA)



Ma et al. (2022) Exploring Advanced Computational Tools and Techniques with Artificial Intelligence and Machine Learning in Operating Nuclear Plants, NUREG/CR-7294, INL/EXT-21-61117. U.S. Nuclear Regulatory Commission.

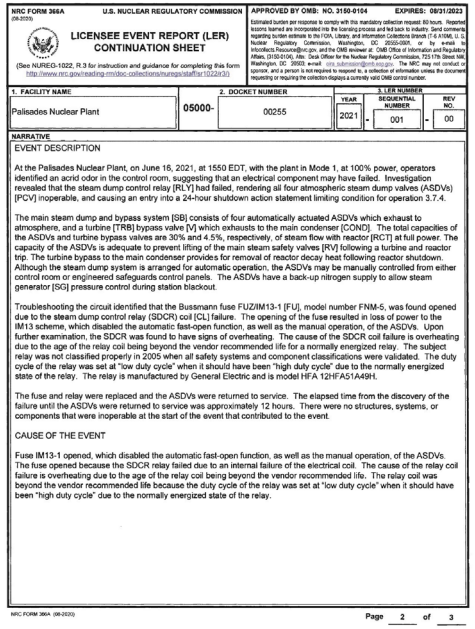
Motivation

- Analyzing free-text OpE data for risk model parameter estimates
  - **What we are doing now**
    - Part of U.S. nuclear industry OpE data are stored and coded by Nuclear Regulatory Commission (NRC) and Idaho National Laboratory (INL) in the NRC Reactor Operational Experience Results and Database (https://nrcoe.inl.gov/ParamEstSpar/) to update and maintain parameter estimates for standardized plant analysis risk (SPAR) models
  - **Current challenges**
    - "Cherry-picking" from an event record
    - Small number of observed failures (i.e., *n* values)
    - Difficulty to justify and expand data applications, e.g., to advanced reactors



Research Focus

- **Using natural language processing (NLP) to enhance OpE text data analysis**
  - Funded by U.S. NRC under Computational Support for Risk Applications Project
  - From ***causal learning*** to ***causal inference***
    - Enhance physical understanding of failure initiation and propagation
    - Facilitate use of non-failure data to complement the limited data pool of failures
    - Support evaluation of applicability of existing data to, e.g., advanced reactors



NRC FORM 366A U.S. NUCLEAR REGULATORY COMMISSION

LICENSEE EVENT REPORT (LER)
CONTINUATION SHEET

(See NUREG-1022, R.3 for instruction and guidance for completing this form)

1. FACILITY NAME	2. DOCKET NUMBER	3. LER NUMBER		
		YEAR	SEQUENTIAL NUMBER	REV NO.
Palisades Nuclear Plant	05000- 00255	2021	- 001	- 00

NARRATIVE

EVENT DESCRIPTION

At the Palisades Nuclear Plant, on June 16, 2021, at 1550 EDT, with the plant in Mode 1, at 100% power, operators identified an acrid odor in the control room, suggesting that an electrical component may have failed. Investigation revealed that the steam dump control relay [RLY] had failed, rendering all four atmospheric steam dump valves (ASDVs) [PCV] inoperable, and causing an entry into a 24-hour shutdown action statement limiting condition for operation 3.7.4.

The main steam dump and bypass system [SB] consists of four automatically actuated ASDVs which exhaust to atmosphere, and a turbine [TRB] bypass valve [V] which exhausts to the main condenser [COND]. The total capacities of the ASDVs and turbine bypass valves are 30% and 4.5%, respectively, of steam flow with reactor [RCT] at full power. The capacity of the ASDVs is adequate to prevent lifting of the main steam safety valves [RV] following a turbine and reactor trip. The turbine bypass to the main condenser provides for removal of reactor decay heat following reactor shutdown. Although the steam dump system is arranged for automatic operation, the ASDVs may be manually controlled from either control room or engineered safeguards control panels. The ASDVs have a back-up nitrogen supply to allow steam generator [SG] pressure control during station blackout.

Troubleshooting the circuit identified that the Bussmann fuse FUZ/IM13-1 [FU], model number FNM-5, was found opened due to the steam dump control relay (SDCR) coil [CL] failure. The opening of the fuse resulted in loss of power to the IM13 scheme, which disabled the automatic fast-open function, as well as the manual operation, of the ASDVs. Upon further examination, the SDCR was found to have signs of overheating. The cause of the SDCR coil failure is overheating due to the age of the relay coil being beyond the vendor recommended life for a normally energized relay. The subject relay was not classified properly in 2005 when all safety systems and component classifications were validated. The duty cycle of the relay was set at "low duty cycle" when it should have been "high duty cycle" due to the normally energized state of the relay. The relay is manufactured by General Electric and is model HFA 12HFA51A49H.

The fuse and relay were replaced and the ASDVs were returned to service. The elapsed time from the discovery of the failure until the ASDVs were returned to service was approximately 12 hours. There were no structures, systems, or components that were inoperable at the start of the event that contributed to the event.

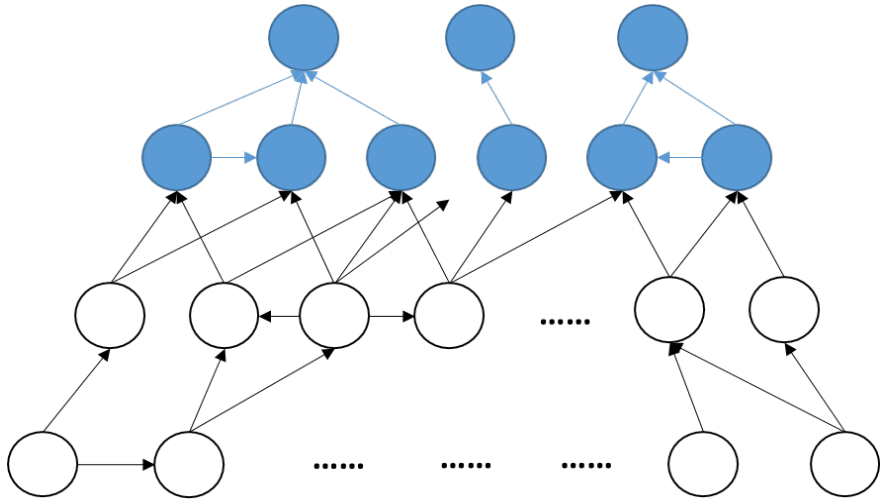
CAUSE OF THE EVENT

Fuse IM13-1 opened, which disabled the automatic fast-open function, as well as the manual operation, of the ASDVs. The fuse opened because the SDCR relay failed due to an internal failure of the electrical coil. The cause of the relay coil failure is overheating due to the age of the relay coil being beyond the vendor recommended life. The relay coil was beyond the vendor recommended life because the duty cycle of the relay was set at "low duty cycle" when it should have been "high duty cycle" due to the normally energized state of the relay.

NRC FORM 366A (08-2020) Page 2 of 3

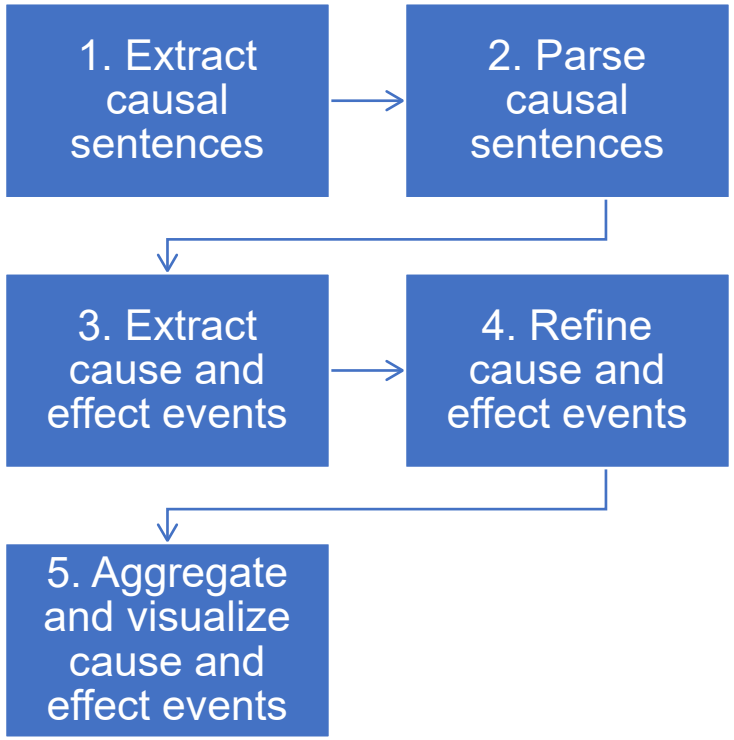
Input: free-text event report

NLP-Enhanced Analysis



Output: directed acyclic graph

Methodological Steps



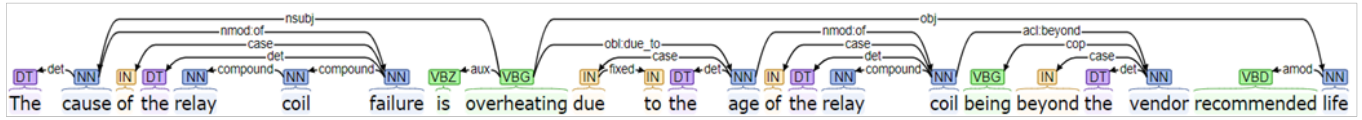
Strategy-Based Approach for Steps 1-3

[' Investigation revealed that the steam dump control relay had failed, rendering all four atmospheric steam dump valves (AS DVs) inoperable', ' The opening of the fuse resulted in loss of power to the IM13 scheme, which disabled the automatic fast-open function, as well as the manual operation, of the ASDVs', ' The cause of the SDCR coil failure is overheating due to th e age of the relay coil being beyond the vendor recommended life for a normally energized relay', ' Troubleshooting the circu it identified that the Bussmann fuse FUZ/IM13-1 [FU], model number FNM-5, was found opened due to the steam dump control rel ay (SDCR) coil [CL] failure', ' The cause of the SDCR coil failure is overheating due to the age of the relay coil being beyo nd the vendor recommended life for a normally energized relay', ' The duty cycle of the relay was set at "low duty cycle" whe n it should have been "high duty cycle" due to the normally energized state of the relay', ' The opening of the fuse resulted in loss of power to the IM13 scheme, which disabled the automatic fast-open function, as well as the manual operation, of th e ASDVs', ' Investigation revealed that the steam dump control relay [RL Y] had failed, rendering all four atmospheric stea m dump valves (ASDVs) [PCV] inoperable, and causing an entry into a 24-hour shutdown action statement limiting condition for

a) Keyword filter result

```
[(13, 13, 'rendering')]
[(19, 19, 'rendering'), (37, 37, 'causing')]
[(6, 6, 'resulted'), (19, 19, 'disabled'), (28, 30, 'as well as')]
[(6, 6, 'resulted'), (19, 19, 'disabled'), (28, 30, 'as well as')]
[(2, 2, 'cause'), (11, 12, 'due to')]
[(6, 6, 'resulted'), (19, 19, 'disabled'), (28, 30, 'as well as')]
[(28, 29, 'due to')]
[(2, 2, 'cause'), (11, 12, 'due to')]
```

b) Tuple information for each sentence



S#	Cause	Keyword	Effect
4	overheating	cause	the SDCR coil failure
4	the age of the relay coil being beyond	due to	overheating

c) Dependencies and relationship extraction for a single sentence

Example Input Data

NRC FORM 366 (08-2020) U.S. NUCLEAR REGULATORY COMMISSION

APPROVED BY OMB: NO. 3150-0104 EXPIRES: 08/31/2023

Estimated burden per response to comply with this mandatory collection request: 80 hours. Reported lessons learned are incorporated into the licensing process and fed back to industry. Send comments regarding burden estimate to the FOIA, Library, and Information Collections Branch (T-6 A10M), U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, or by e-mail to Infocollects.Resource@nrc.gov, and the OMB reviewer at: OMB Office of Information and Regulatory Affairs, (3150-0104), Attn: Desk at: ora_submission@omb.eop.gov. The NRC may not conduct or sponsor, and a person is not required to respond to, a collection of information unless the document requesting or requiring the collection displays a currently valid OMB control number.

LICENSEE EVENT REPORT (LER)

(See Page 3 for required number of digits/characters for each block)

(See NUREG-1022, R.3 for instruction and guidance for completing this form http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1022/r3/)

1. Facility Name	2. Docket Number	3. Page
Palisades Nuclear Plant	05000 255	1 OF 3

4. Title
Atmospheric Steam Dump Valves Inoperable Due to Relay Failure

5. Event Date			6. LER Number			7. Report Date			8. Other Facilities Involved	
Month	Day	Year	Year	Sequential Number	Revision No.	Month	Day	Year	Facility Name	Docket Number
06	16	2021	2021	- 001 -	00	08	13	2021	N/A	05000
									Facility Name: N/A	Docket Number: 05000

9. Operating Mode	10. Power Level
Mode 1	100

11. This Report is Submitted Pursuant to the Requirements of 10 CFR §: (Check all that apply)

10 CFR Part 20	☐ 20.2203(a)(2)(vi)	☐ 50.36(c)(2)	☐ 50.73(a)(2)(iv)(A)	☐ 50.73(a)(2)(x)
☐ 20.2201(b)	☐ 20.2203(a)(3)(i)	☐ 50.46(a)(3)(ii)	☐ 50.73(a)(2)(v)(A)	10 CFR Part 73
☐ 20.2201(d)	☐ 20.2203(a)(3)(ii)	☐ 50.69(g)	☐ 50.73(a)(2)(v)(B)	☐ 73.71(a)(4)
☐ 20.2203(a)(1)	☐ 20.2203(a)(4)	☐ 50.73(a)(2)(i)(A)	☐ 50.73(a)(2)(v)(C)	☐ 73.71(a)(5)
☐ 20.2203(a)(2)(i)	10 CFR Part 21	☐ 50.73(a)(2)(i)(B)	☑ 50.73(a)(2)(v)(D)	☐ 73.77(a)(1)(i)
☐ 20.2203(a)(2)(ii)	☐ 21.2(c)	☐ 50.73(a)(2)(i)(C)	☐ 50.73(a)(2)(vii)	☐ 73.77(a)(2)(i)
☐ 20.2203(a)(2)(iii)	10 CFR Part 50	☐ 50.73(a)(2)(ii)(A)	☐ 50.73(a)(2)(viii)(A)	☐ 73.77(a)(2)(ii)
☐ 20.2203(a)(2)(iv)	☐ 50.36(c)(1)(i)(A)	☐ 50.73(a)(2)(ii)(B)	☐ 50.73(a)(2)(viii)(B)	
☐ 20.2203(a)(2)(v)	☐ 50.36(c)(1)(ii)(A)	☐ 50.73(a)(2)(iii)	☐ 50.73(a)(2)(ix)(A)	

☐ OTHER (Specify here, in abstract, or NRC 366A).

12. Licensee Contact for this LER

Licensee Contact	Phone Number (Include area code)
Barbara Dotson, Regulatory Assurance Manager	269-764-2265

13. Complete One Line for each Component Failure Described in this Report

Cause	System	Component	Manufacturer	Reportable to IRIS	Cause	System	Component	Manufacturer	Reportable to IRIS
E	SB	RLY	G080	Y	E	SB	FU	B569	Y

14. Supplemental Report Expected		15. Expected Submission Date	Month	Day	Year
☑ No	☐ Yes (If yes, complete 15. Expected Submission Date)				

16. Abstract (Limit to 1560 spaces, i.e., approximately 15 single-spaced typewritten lines)

At the Palisades Nuclear Plant, on June 16, 2021, at 1550 EDT, with the plant in Mode 1, at 100% power, operations identified an acrid odor in the control room. Investigation revealed that the steam dump control relay had failed, rendering all four atmospheric steam dump valves (ASDVs) inoperable.

The relay was replaced and the ASDVs were returned to service. The plant remained stable in Mode 1 at 100% power throughout the event. The safety significance of this event was minimal. This event is reportable in accordance with 10 CFR 50.73(a)(2)(v)(D) as an event or condition that at the time of discovery could have prevented the fulfillment of the safety function of structures or systems that are needed to mitigate the consequences of an accident.

NRC FORM 366A (08-2020) U.S. NUCLEAR REGULATORY COMMISSION

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Troubleshooting the circuit identified that the Bussmann fuse FUZ/IM13-1 [FU], model number FNM-5, was found opened due to the steam dump control relay (SDCR) coil [CL] failure. The opening of the fuse resulted in loss of power to the IM13 scheme, which disabled the automatic fast-open function, as well as the manual operation, of the ASDVs. Upon further examination, the SDCR was found to have signs of overheating. The cause of the SDCR coil failure is overheating due to the age of the relay coil being beyond the vendor recommended life for a normally energized relay. The subject relay was not classified properly in 2005 when all safety systems and component classifications were validated. The duty cycle of the relay was set at "low duty cycle" when it should have been "high duty cycle" due to the normally energized state of the relay. The relay is manufactured by General Electric and is model HFA 12HFA51A49H.

The fuse and relay were replaced and the ASDVs were returned to service. The elapsed time from the discovery of the failure until the ASDVs were returned to service was approximately 12 hours. There were no structures, systems, or components that were inoperable at the start of the event that contributed to the event.

CAUSE OF THE EVENT

Fuse IM13-1 opened, which disabled the automatic fast-open function, as well as the manual operation, of the ASDVs. The fuse opened because the SDCR relay failed due to an internal failure of the electrical coil. The cause of the relay coil failure is overheating due to the age of the relay coil being beyond the vendor recommended life. The relay coil was beyond the vendor recommended life because the duty cycle of the relay was set at "low duty cycle" when it should have been "high duty cycle" due to the normally energized state of the relay.

NRC FORM 366A (08-2020) Page 2 of 3

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1. FACILITY NAME	2. DOCKET NUMBER	3. LER NUMBER		
		YEAR	SEQUENTIAL NUMBER	REV NO.
Palisades Nuclear Plant	05000- 255	2021	- 001	- 00

NARRATIVE

ASSESSMENT OF SAFETY CONSEQUENCES

The actual consequence of the failure of the SDCR, which was a short-circuit in the relay coil, was overcurrent in the IM13 circuit and opening of fuse FUZ/IM13-1. This resulted in loss of power to the IM13 scheme, which disables the automatic fast-open function of the ASDVs and disables manual operation of the ASDVs. There were no other actual consequences to the general safety of the public, nuclear safety, industrial safety, or radiological safety for this event as the plant remained in steady-state full power operation.

CORRECTIVE ACTIONS

The fuse and relay were replaced. The preventive maintenance optimization code is being revised to show the relay as high duty cycle as it is continuously energized. This action will appropriately prioritize maintenance for the relay and prevent recurrence of this failure.

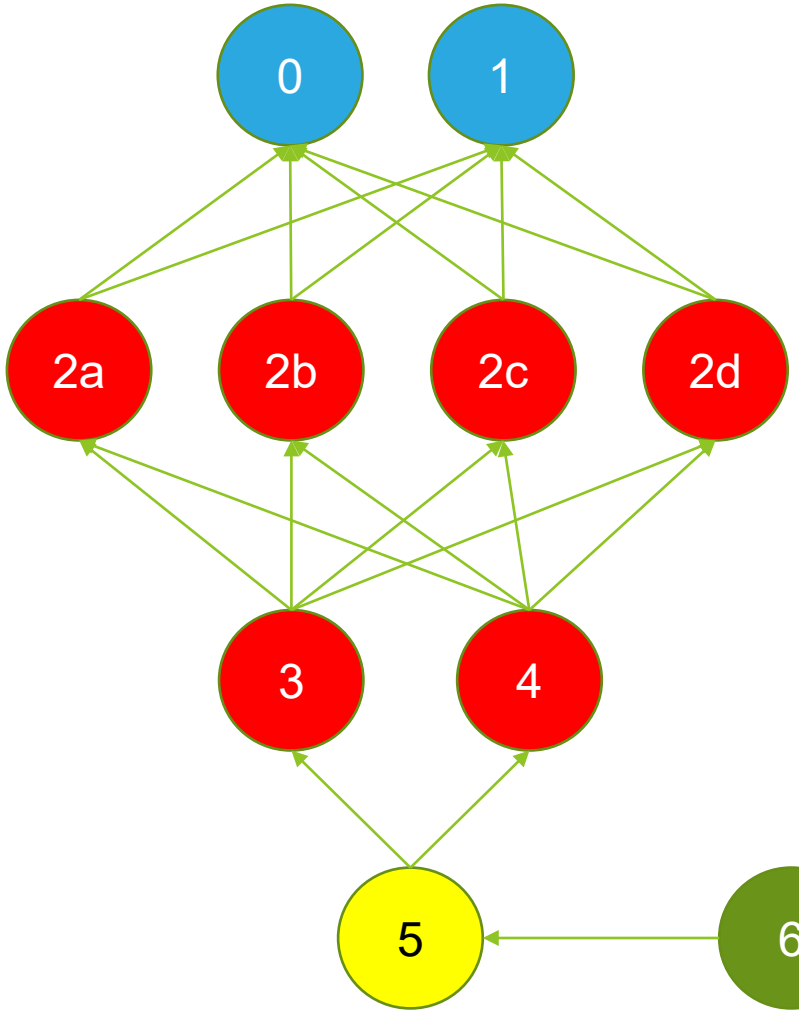
PREVIOUS SIMILAR EVENTS

None.

NRC FORM 366A (08-2020) Page 3 of 3

- Our NLP tool can take in a variety of files, such as PDF, text, and csv

Results (One Event Report)



0. An acrid odor in control room
1. Entry into a 24-hour shutdown action statement
2. Four atmospheric steam dump valves inoperable
3. Valve automatic operation disabled
4. Valve manual operation disabled
5. Fuse opened
6. Steam dump control relay coil failure
7. Relay coil overheating
8. Relay coil age being beyond the vendor recommended life
9. Wrong determination of relay duty cycle (high vs. low)

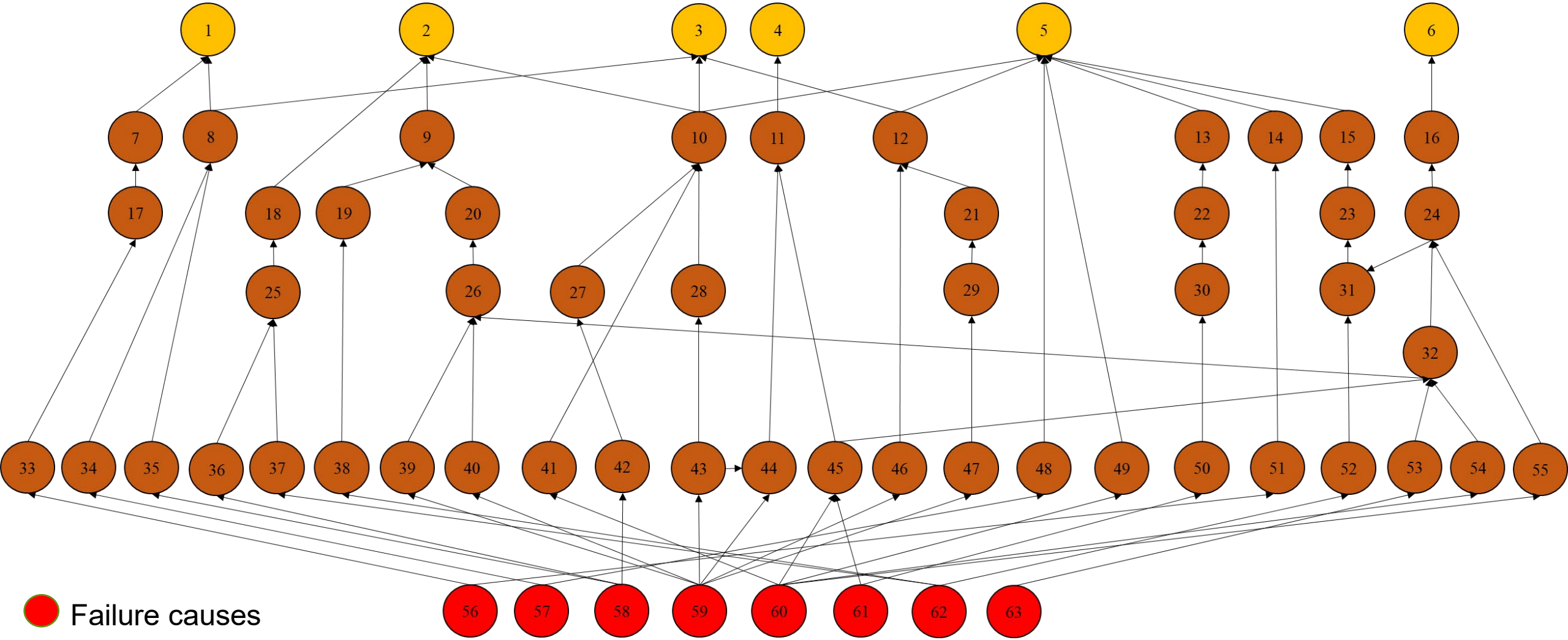
Consequences

Valve

Fuse

Relay

Results (Twenty Event Reports)



- Failure causes
- Failure modes
- Not explicitly stored in current NRC database yet

Summary and Next Steps

- **Summary**
  - Developed an NLP tool to extract and aggregate causal relations from multiple reports
    - Input: event narratives
    - Output: a causal network representing failure initiations and propagations
- **Now working on**
  - Transition from current rule-based approach to machine-learning (ML)-based models
    - To accommodate the need of large-quantity analysis for inference model establishment
    - To leverage existing ML-based NLP models in other domains (e.g., medical) based on transfer learning
  - Developing a labeled benchmark data set to serve ML model training
    - ~100 motor-operated valve failure records
    - Semi-manually labeled by analysts
      - Powered by a web-based text labeling tool that we recently developed
  - Transition from causal learning to causal inference model development

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Backup Slide – Results (Twenty Event Reports)

No.	Event	No.	Event	No.	Event
1	Valve wrongly opened	22	Torque switch failed to close	43	Inappropriate manipulation
2	Valve failed to open	23	Shaft disengaged	44	Loose fuse connection
3	Valve wrongly closed	24	Fatigue	45	Vibrations
4	Valve status unstable	25	Foreign material in a contactor	46	Wrong bolt installed
5	Valve failed to close	26	Weld failed	47	Foreign materials left
6	Valve leakage	27	Flow switch failed	48	Valve unable to be closed at normal force
7	Load driver wrongly activated	28	Relay wires lifted and incorrectly landed	49	Valve coasting further opened
8	Positioner failed	29	One phase of power inhibited, and other phases experienced high amps	50	Steam leak from nearby
9	Valve stem rotation	30	Torque switch corrosion	51	Lack of filtration device
10	Relay failed	31	Roll/shear pin broken	52	Inadequate preventive maintenance frequency
11	Power supply interrupted	32	Overstress	53	Contacts between parts
12	Motor operator control failed	33	Suppressors failed	54	Binding
13	Valve grounding	34	Pilot valve stuck	55	Subpart displacement
14	Debris from control air	35	Wear	56	Random failure
15	Valve actuator failed	36	Contactor susceptible to foreign material	57	Manufacturing deficiency
16	Vent line crack	37	Inadequate inspection procedure	58	Design deficiency
17	Circuits energized	38	Incomplete preventive maintenance procedure	59	Human error
18	Contactor stuck	39	Inadequate performance monitoring	60	Degradation
19	Torque switch arm disengaged from stem key	40	Ineffective troubleshooting	61	Environmental impact
20	Anti-rotation key dropped out	41	Loose sliding link	62	Organizational deficiency
21	Thermal overload device tripped	42	Internal water leakage	63	Installation error