Risk, Reliability and Resilience of Engineered Systems

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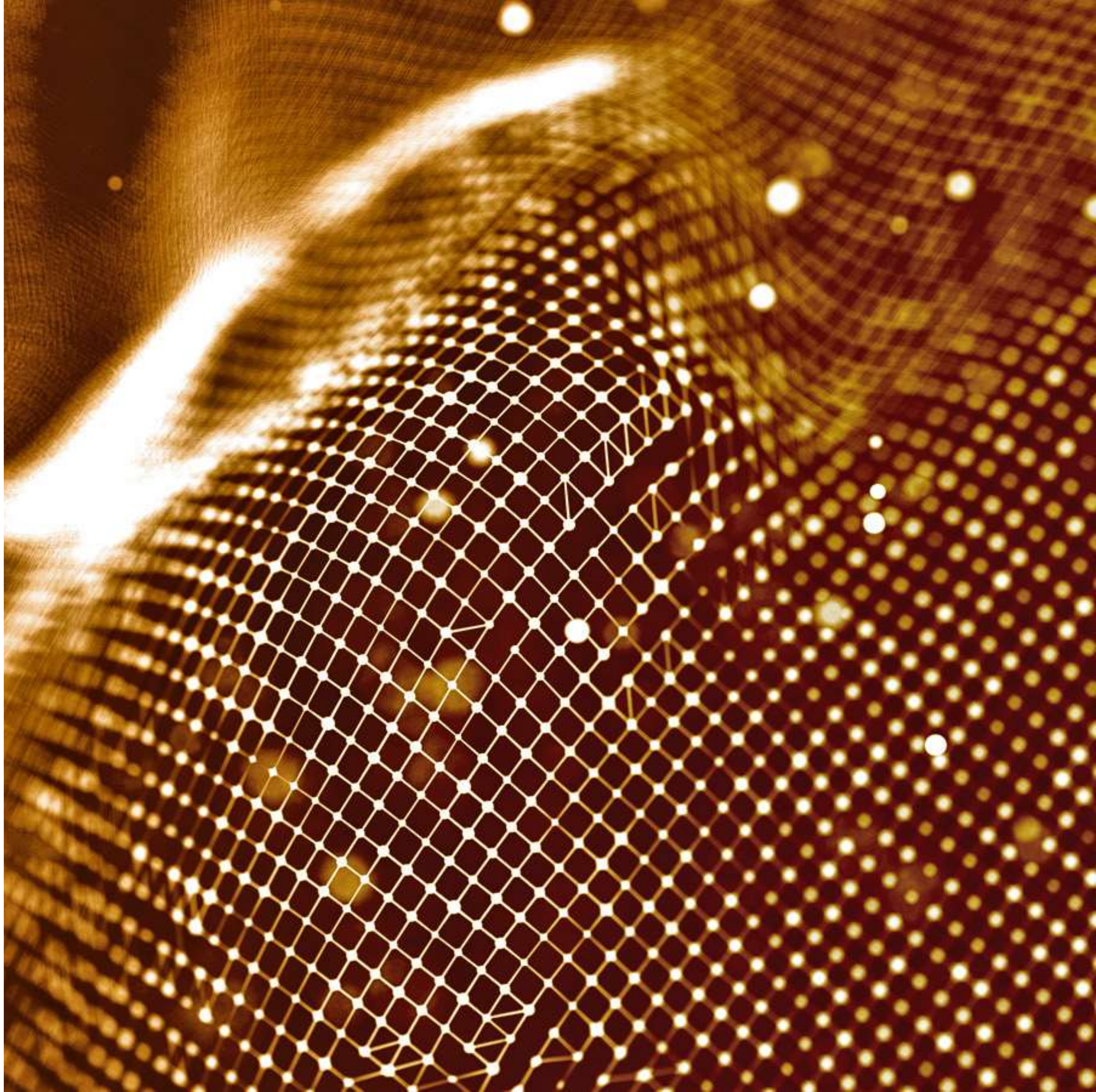


PNNL is operated by Battelle for the U.S. Department of Energy

PNNL Experience with Risk-Informed Resilience Planning

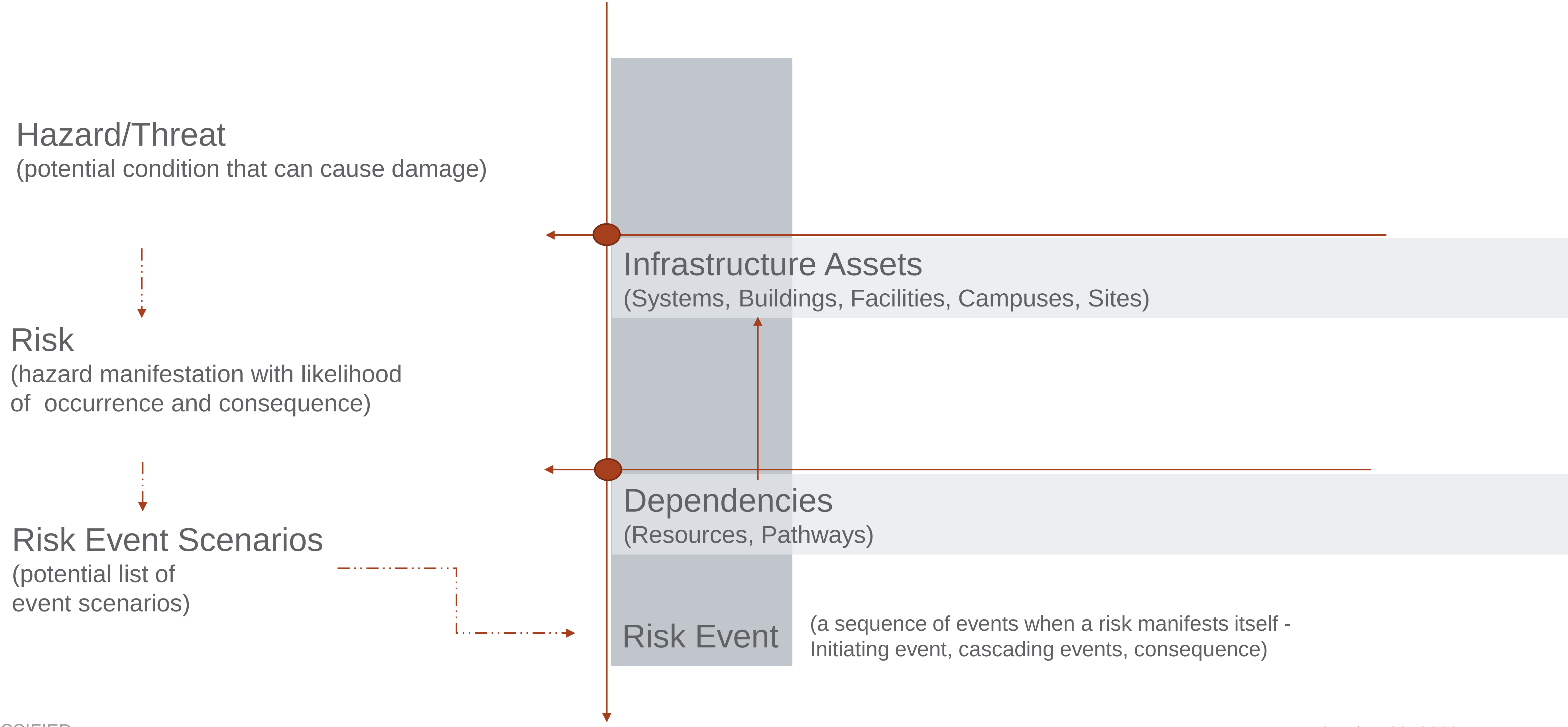
- PNNL has supported the following resilience planning efforts for various organizations

  - Technical Resilience Navigator (TRN) for the Federal Energy Management Program (DOE EERE)
    - ✓ https://trn.pnnl.gov/

  - Army Installation Energy and Water Resilience Assessment Guide and Army Guidance for Installation Energy and Water Plans (IEWPs)

  - Resilience planning against low-probability, high consequence power grid events for the Office of Electricity (DOE OE)

Infrastructure is Exposed to Multiple Hazards



Risk in the Context of Resilience

TIMELINE → Operational Period → Contingency Period → Post-recovery Period → *(what is observed)*

SERVICES → baseline service (operational metrics) | contingency service (contingency metrics) | transitional service (post-contingency metrics) *(what is served)*

ACTIONS → preparedness | response | long-term recovery operations *(what is done)*

↓ Risk

RISK METRIC (Operational/Contingency) → Initiator Likelihood x Facility Failure Likelihood x Consequence Severity x Consequence Duration

e.g. once in 300 yrs | 10% | 1MW | 3 hr | *(MWh/yr)*

↓ Risk Reduction
Exhibits Resilient System Characteristics

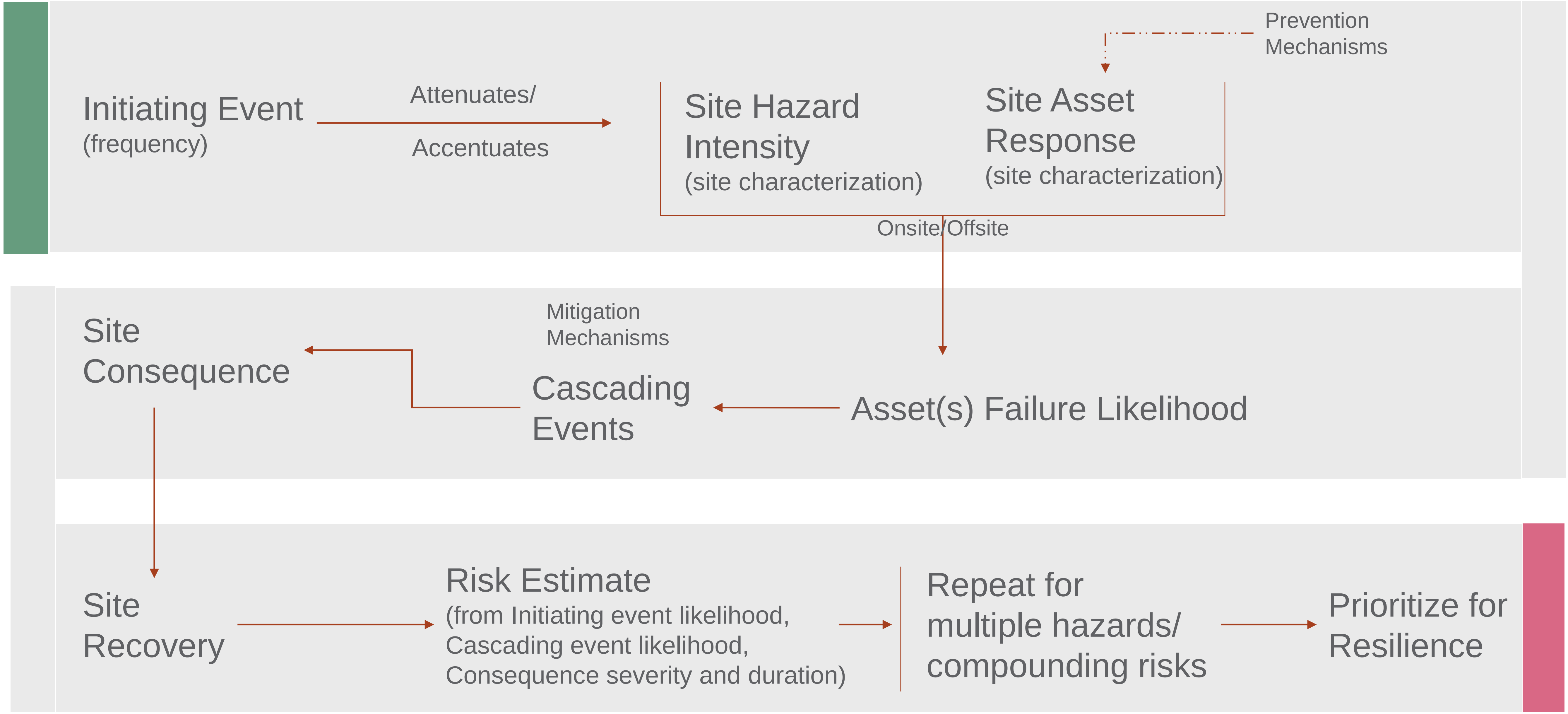
RESILIENCE → Missions carried on with Business Continuity *(what is strived for)*
despite subjectivity to operational and contingency constraints

RESILIENCE METRICS → Robustness, Rapid Recovery, Adaptability, Absorption Capacity, … *(what to measure)*
Measure deviation in / ratio of metrics for the contingency period relative to operational conditions.
e.g. relative to service rendered, recovery time, limited preventive mechanisms and mitigation strategies

ACTIONS that Enhance Resilience
(come from multiple directions)

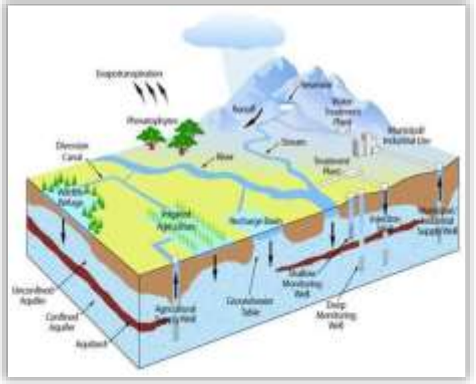
Risk Engineering (scientific agencies, insurance engineers)	-Identify and predict risks -Identify prevention mechanisms and mitigation strategies -risk-informed resilience engineering
Reliability Engineering (designers, manufacturers, operators, reliability and quality engineers)	-Design for reliability (redundancy, stress resistance, layers of protection) -Ensure availability (reduced downtime) and maintainability (repair, prognostic maintenance) -Avoid overlap between operational downtime and a risk event -Situational awareness -reliability-centered resilience engineering
Emergency Preparedness (emergency planners)	-Planning, training, drills -resilience preparedness
Disaster Response (first responders)	-Operator response -Evacuation, search and rescue -disaster resilience
Policy-making (policy makers, law makers, professional associations)	-Inform policies, laws, regulations, standards, codes -resilience-based policy-making
Community Involvement	-Volunteering, awareness, education

Methodology – Risk-informed Resilience



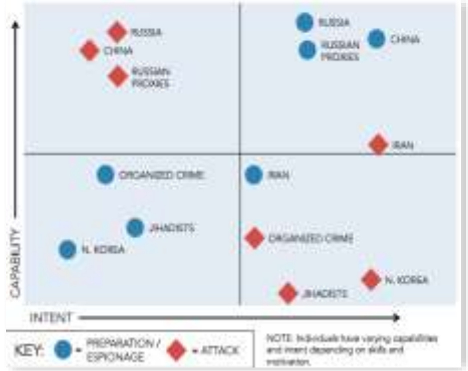
Veeramany, A., Unwin, S.D. *et al*., 2016. Framework for modeling high-impact, low-frequency power grid events to support risk-informed decisions. International journal of disaster risk reduction, 18, pp.125-137.
Veeramany, A. *et al*., 2017. Trial implementation of a multi-hazard risk assessment framework for high-impact low-frequency power grid events. IEEE Systems Journal, 12(4), pp.3807-3815.

Source and Site Characterization Modeling



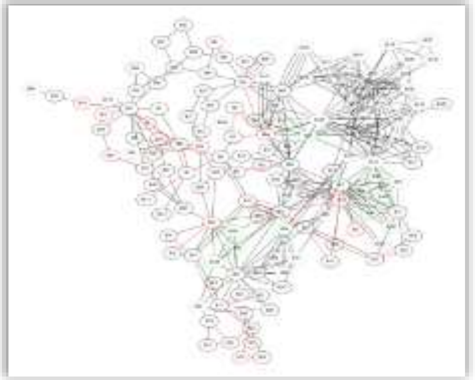
Natural Hazard Characterization

wildfire model (USFS)
hurricane model (NOAA)
hydrology model (USGS, DHS FEMA)
seismic hazard model (USGS, DHS)
tsunami model (DHS FEMA)
disease spread (CDC/CommunityFlu)



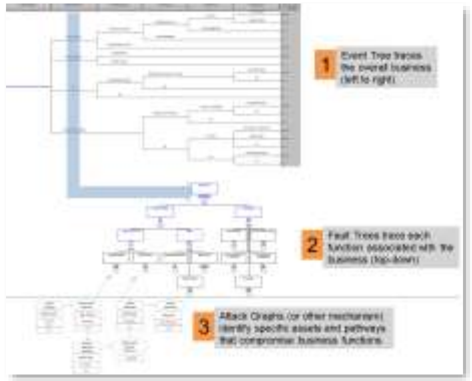
Threat Characterization

intent, motivation, sophistication, capabilities
cyber and physical threats (DHS CISA)
chemical, biological, radiological, and nuclear (DHS S&T/PANTHR)



Network Assessment

connected facilities
electric power grid
communications
transportation

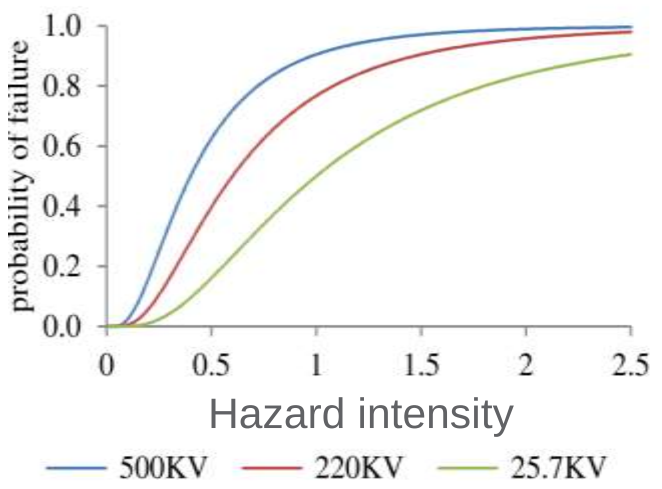


Risk/Reliability Assessment

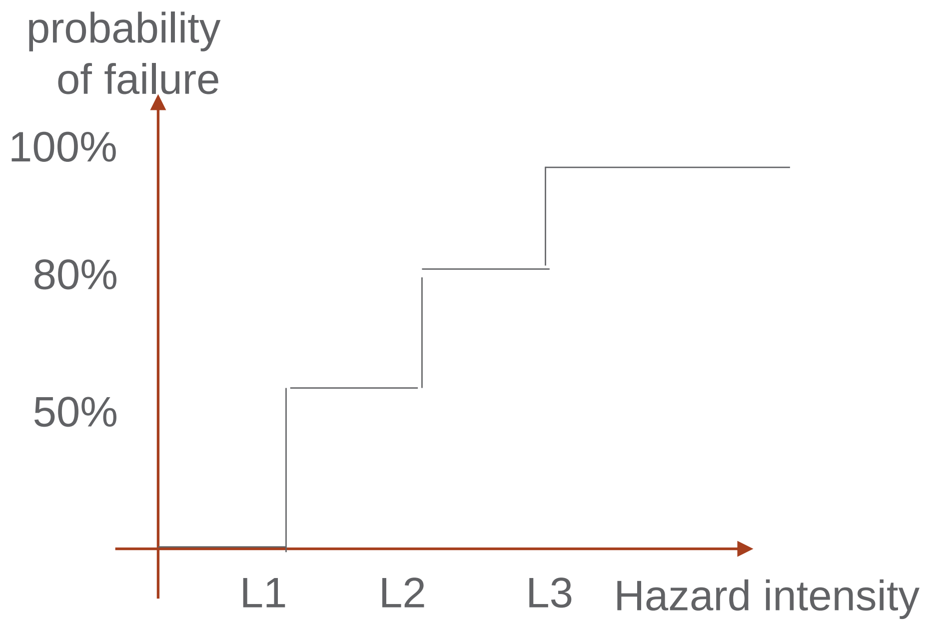
fragility curves (stress-oriented)
fault trees (deductive)
event trees (inductive)
reliability blocks (goal-oriented)
game theory (adversarial)

USFS: U.S. Forest Service
NOAA: National Oceanic and Atmospheric Administration
USGS: U.S. Geological Survey
DHS: Department of Homeland Security
CDC: Center for Disease Control and Prevention
FEMA: Federal Emergency Management Agency
CISA: Cyber and Infrastructure Security Agency
PANTHR: Probabilistic Analysis of National Threats Hazards and Risks

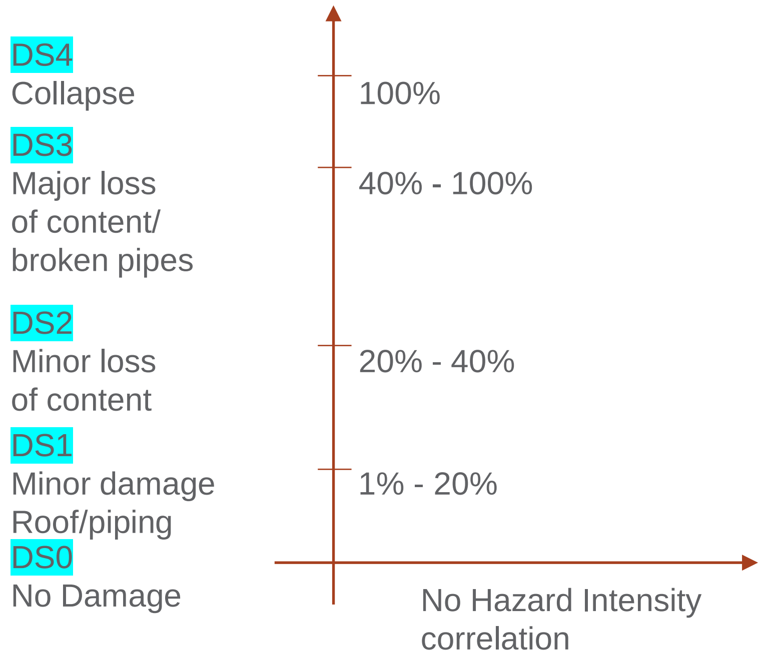
Asset Failure Likelihood Estimation – Spectrum of Sophistication



Fragility curves are available in limited hazard/asset combinations.



When precise fragility curves are not available, use elicitation techniques to devise an approximate step function.



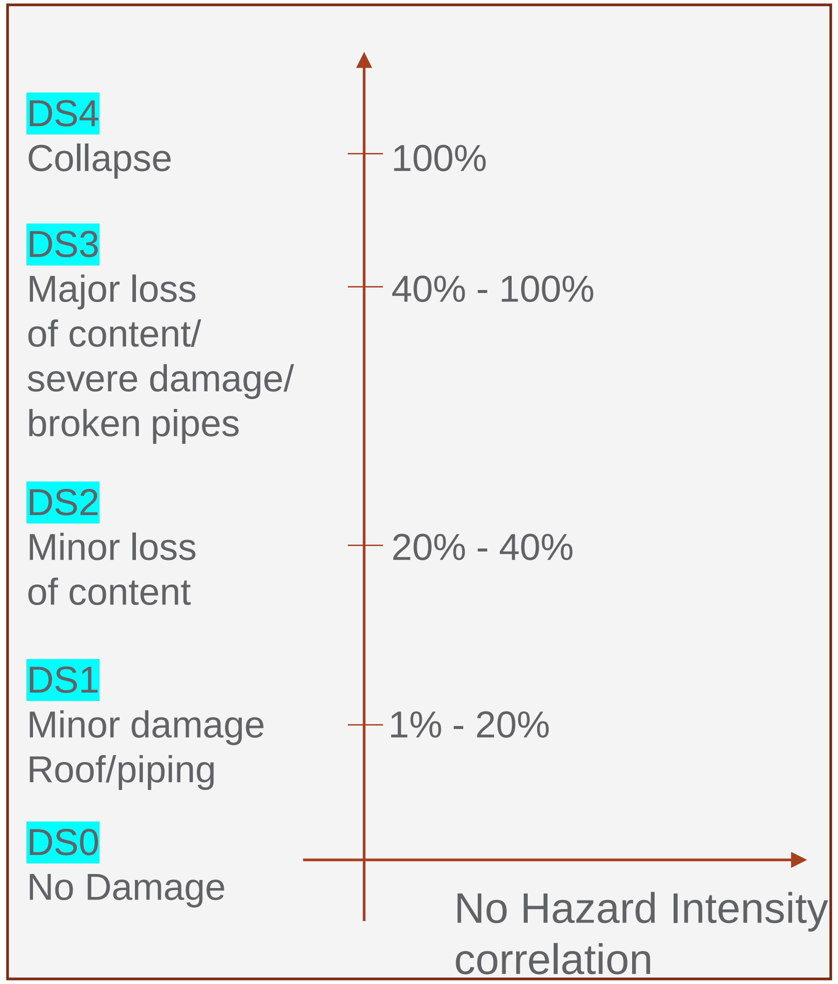
When precise fragility curves are not available, use damage states. Limited asset/damage state combinations are available.

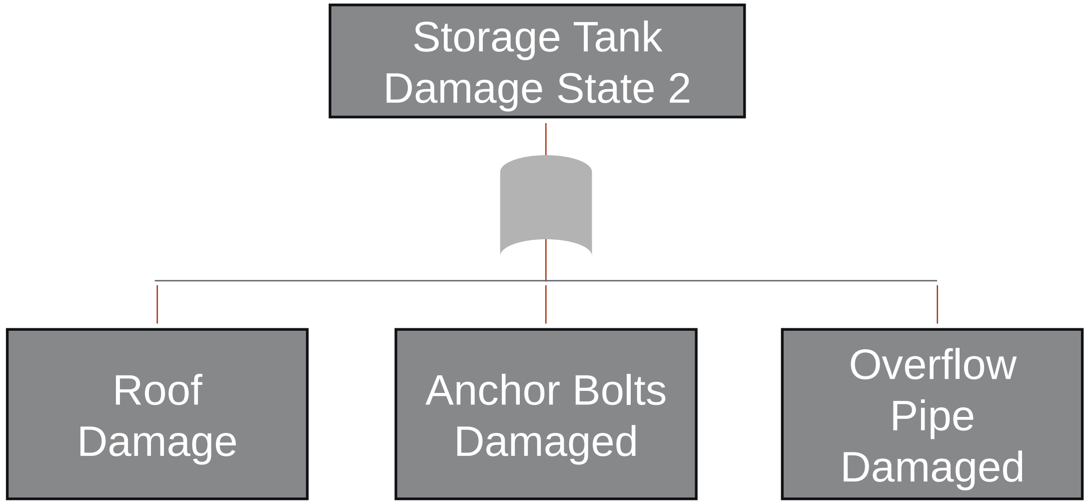
Veeramany, A. *et al*., 2017. Trial implementation of a multi-hazard risk assessment framework for high-impact low-frequency power grid events. IEEE Systems Journal, 12(4), pp.3807-3815.

Fragility Databases

Organization	Hazard	Assets	Intensity Parameter	Notes
DHS FEMA	Hazus-Earthquake	Buildings, non-structural elements: electrical, mechanical, piping, ducts Roads, bridges, tunnels, railways, fuel facilities	Peak Ground Acceleration (g)	Probability of failure for given acceleration
DHS FEMA	Hazus-Flooding	Pipelines, water treatment plants, plants, stations, tanks, substations	Inundation depth (ft)	% damage by depth of flooding
DHS FEMA	Hazus-Tsunami	Wooden house, concrete residential, R/C steel frame	Water depth (ft)	Probability of failure for given water depth
Johns Hopkins, Buffalo, Princeton	Fire	Office, dwelling, library, (multi-storied) with and without sprinklers, steel frame buildings	Fire load (MJ/m^2)	DOI 10.1007/s10694-018-0764-5
GIT, OSU	Wind	Wooden structures	Wind speed (m/s)	DOI: 10.1061/(ASCE)0733-9445(2004)130:12(1921)
Canterbury, NZ	Volcanic	Power, water, wastewater, transportation, HVAC	Tephra thickness (mm)	DOI:10.1186/s13617-017-0065-6
USACE	Seismic, Wind, Flood, Fire	References to several technical papers		ERDC SR-10-1 July 2010

Fragility Curves Unavailable - Damage State Estimation



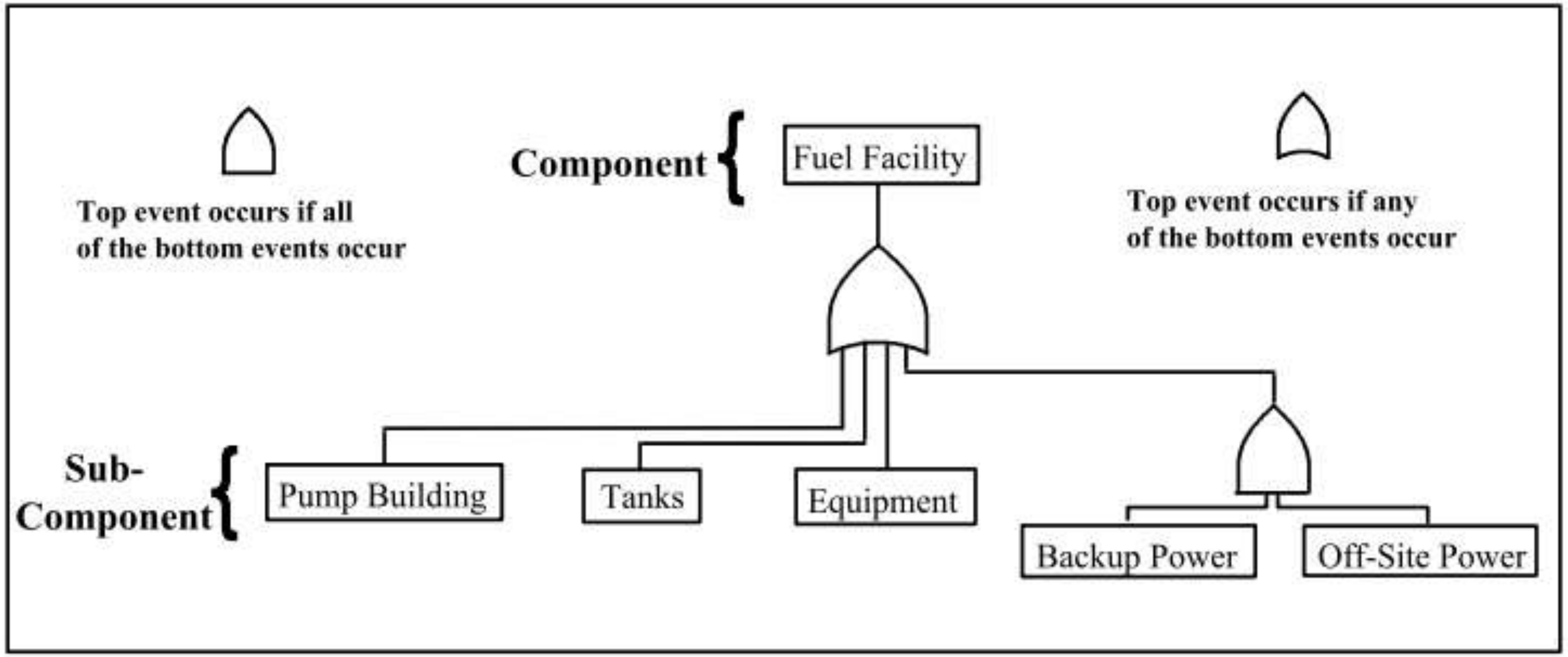


Organization	Hazard	Assets	Notes
DHS FEMA Hazus-MH	Seismic Hurricane Flood Tsunami	Buildings, piping, ducts, roads, bridges, tunnels, railways, fuel facilities, water treatment plants, stations, tanks, substations	https://toolkit.climate.gov/tool/hazus
European Commission SYNER-G	Seismic	Oil & gas, electric power, water, sewage, transportation, infrastructure, hospitals, fire fighting	vce.at/SYNER-G/

- Asset damage states are available, but not asset failure likelihood nor as a function of hazard intensity
- Site-wide consequence modeling is needed after this step

Alexoudi, M., Pitilakis, K. and Souli, A., 2010. Fragility functions for water and wastewater system elements, deliverable D3. 5 SYNER-G project: Systemic seismic vulnerability and risk analysis for buildings, lifeline networks and infrastructures safety gain. *Aristotle University of Thessaloniki*.

Site Response –
Reliability Technique for Facilities



From DHS FEMA Hazus-MH Technical Manual

- Simulate multiple failure combinations in a hazard agnostic way and backtrack all possible facility end states (or)
- Assign damage likelihood to each asset given the hazard conditions from the fragility curves (or)
- Assign damage state to each asset given the hazard conditions and determine facility end state

Conclusion

- Infrastructure can be exposed to several hazards
- Risk is a basis for measuring resilience improvement
  - Resilience targets both missions and business continuity
  - There's a stable of established and proven methods for risk quantification
  - Resilience metrics, where they exist, are diverse and often don't allow direct comparison of disparate resilience options.
- There are diverse means of achieving resilience
  - Risk and reliability engineering, emergency preparedness, disaster response, …
- A risk-informed approach to resilience supports resilience prioritization
  - Between hazards, there is a wide range of maturity in available hazard and fragility information
  - Helps select among resilience enhancement options

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Thank you