Quantifying Risk of Cascading Failures in Large-Scale Hydrogen Storage Systems

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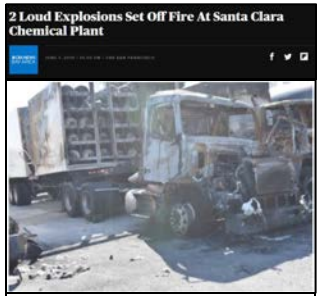
Introduction

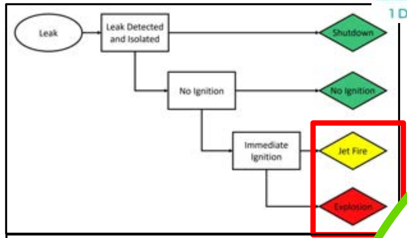
The Department of Energy launched its clean energy Hydrogen Shot in 2021.

Hydrogen is flammable, and may ignite or explode if leaks occur in an H_2 storage system. These **hazards can be fatal** to operators and others in proximity.



Headline and image of the damage on a trailer from cascading leaks that occurred at a Santa Clara hydrogen refueling facility in 2019.

Past incidents of hydrogen leaks show that a fire or explosion from an initial leak can lead to "cascading" leaks in other parts of the system, leading to the risk of ignition at multiple points.



Potentially fatal consequences of a hydrogen leak.

Existing tools like the **HyRAM+ software** provide a method of calculating risk to workers in terms of **fatality frequency per year** for a **single H_2 leak**.

The goal of this project is to design a framework to calculate total risk to workers in an H_2 storage facility where cascading leaks are considered. **The risk model capability for hydrogen does not currently exist in literature.**

Research Highlights and Impact

- Designed an event sequence diagram approach to model cascading leaks in hydrogen storage and dispensing systems.
- Created a framework to calculate overall risk for an exposed individual.
- Types of calculable results include risk in fatality frequency per year for each leak, consequence type, and most sensitive parameters.

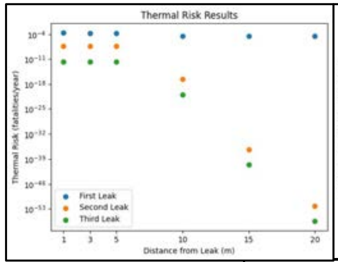
This novel cascading failure risk framework can inform safe design of future hydrogen facilities.

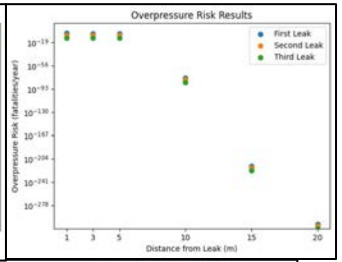
Results

The first two graphs show **thermal and overpressure risk results** (from hydrogen fires and explosions, respectively) for an individual in six locations between 1 and 20 meters in front of each leak.

The results for this run show that additional thermal risk from cascaded failures drops off at distances of 10 meters from the leak and farther.

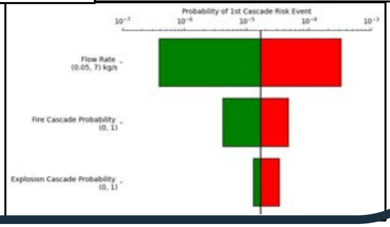
Cascaded leaks tend to have similar overpressure risk to initial leaks when 100% leaks dominate overall risk.





Sensitivity studies of the model can show which parameters most affect the probability that a cascading failure occurs.

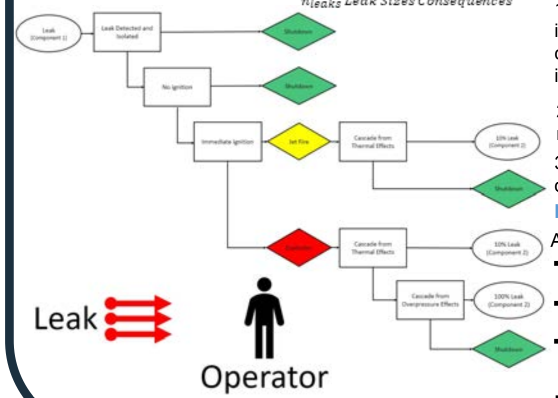
Here, the probability of a cascade failure occurring is most sensitive to the flow rate of hydrogen out of the initial leak. This is because the flow rate determines the probability that the first leak will ignite.



Materials And Methods

HyRAM+ Hydrogen Plus Other Alternative Fuels Risk Assessment Models

$$Total\ Risk = \sum_{n_{leaks}} \sum_{Leak\ Sizes} \sum_{Consequences} Frequency \times Probability\ of\ Fatality$$



1. The **event sequence diagram** currently implemented in HyRAM+ was modified to consider a cascading leak from either an initial jet fire or explosion.

2. The associated logic was coded into a Jupyter notebook.

3. HyRAM+ was used to calculate the risk of each leak based on the **fuel conditions** (temperature, pressure) and selected **physics models for heat flux and overpressure.**

Assumptions:

- System components are much closer to each other than to the operator.
- The leaks all point directly at the operator (worst-case scenario).
- Fires cause medium-sized cascaded leaks (orifice area=10% of pipe cross-section).
- Explosions cause full-bore cascaded leaks (orifice area=100% of pipe).

Discussion and Conclusion

The cascade failure framework currently produces results with trends that make logical sense based on user inputs. Potential uses include **informing safety measures and mitigations to reduce overall risk** and **regulating setback distances between components**, especially as systems are scaled up.

<u>Current model limitations, challenges, and potential improvements:</u>

- The probabilities that a cascade will occur from a jet fire or from an explosion are user inputs. **Ideally, inputs would be based on empirical data**. However, data for cascading leaks in hydrogen storage systems is unavailable or does not currently exist.
- Risk can currently be calculated for an individual. Hydrogen facilities have multiple operators and the risk from large scale systems may affect populations outside of the facility. Going forward, **it may be useful to consider societal or population risk.**
- The assumption that a jet fire can cause a 10% leak and an explosion can cause a 100% leak in another component is a hypothesis. **Fragility modeling of component materials and their thermal and strength properties can yield more accurate leak sizes**. This modeling should also consider the phase of hydrogen stored. For example, jacketed liquid systems may have smaller leaks or cascading failure probabilities than gaseous ones.

U.S. DEPARTMENT OF ENERGY

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Santa Clara incident headline: https://www.cbsnews.com/sanfrancisco/news/explosion-fire-at-santa-clara-chemical-plant/, Santa Clara incident truck image: https://h2tools.org/sites/default/files/2021-06/AP_Santa_Clara_Incident_Review_Report_Rev1.pdf, HyRAM+ technical manual: https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hyram/