Large-Scale Hydrogen Storage - Risk Assessment Seattle City Light and Port of Seattle

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2024 Annual Merit Review and Peer Evaluation Meeting

AMR Project
SCS034

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Project Goal:
Risk Assessment of Large-Scale Hydrogen Storage

- The projects helps Utilities and Ports in undertaking risk assessments that yield public safety risk metrics and in effective stakeholder engagement

- The project applies a series of risk assessment techniques from ISO 31010 towards understanding hydrogen plant systems, their failure modes, and safety risks.

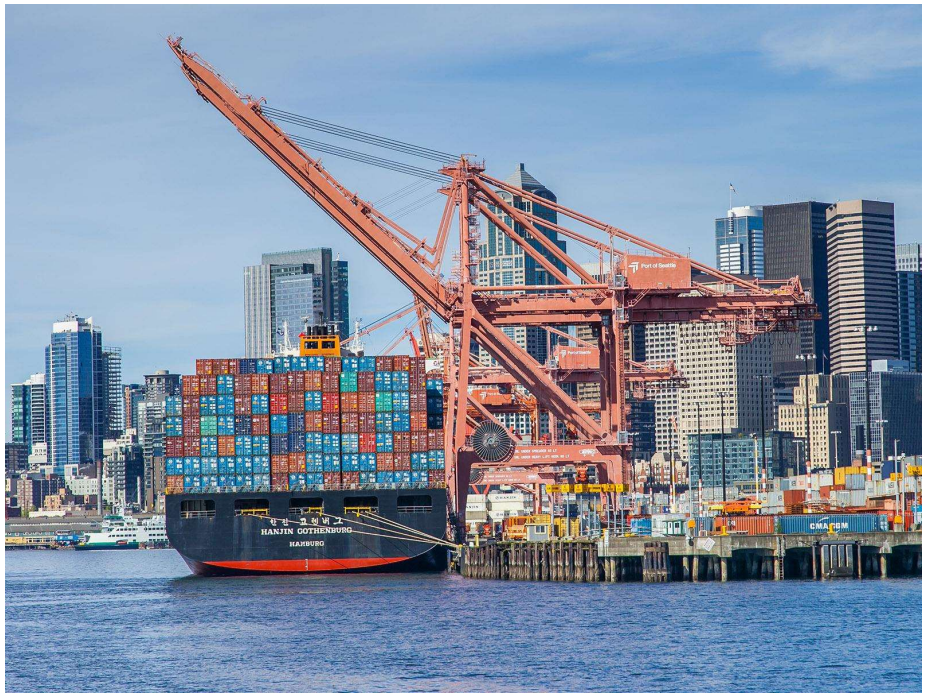


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Project Overview:
Q3 Underway, Manageable Barriers, On Target

Timeline and Budget

- Project Start Date: 09/30/2022
- Project End Date: 10/16/2024

- Total Project Budget: $880,000
  - Total DOE Share: $770,000
  - Total Cost Share: $110,000

- Project Resource Allocation
  - PNNL: $400,000
  - SNL: $370,000
  - SCL (Cost Share): $75,000
  - Port (Cost Share): $35,000

- Total FY24 DOE Funds Spent*: $530,371
- Total Cost Share Funds Spent*: $42,760

* As of 03/01/2024

Barriers

- Exact system architecture is unavailable.
- There is uncertainty in associating multiple hydrogen carriers with various maritime applications.
- There is need for increasing public confidence and understanding in hydrogen as a fuel.

Targets

- Identify relevant public safety risk metrics, compare hydrogen carriers, and engage with community-facing agencies.

Partners

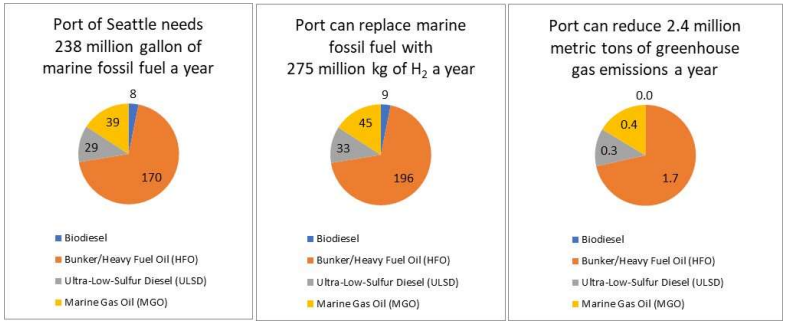
- Arun Veeramany (PI, PNNL)
- Brian Ehrhart (PI, SNL)
- Seattle City Light
- Port of Seattle

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Potential Impacts:
Decarbonization, Risk Assessment, Stakeholder Engagement

Barriers	Impacts
Exact system architecture is unavailable	The project illustratively quantifies risk in the presence of uncertainties for hydrogen systems deployed in urban-industrial settings.
There is uncertainty in associating multiple hydrogen carriers with various maritime applications.	Trade-offs in choice of hydrogen carriers for maritime applications is made available.
Public confidence and understanding in hydrogen as a fuel	The project sets an example for community-facing agencies in increasing public capacity for dialogue and engagement.

Decarbonization The project is supporting the decarbonization goals of the Port and SCL by determining the hydrogen equivalent of their current fossil fuel needs.



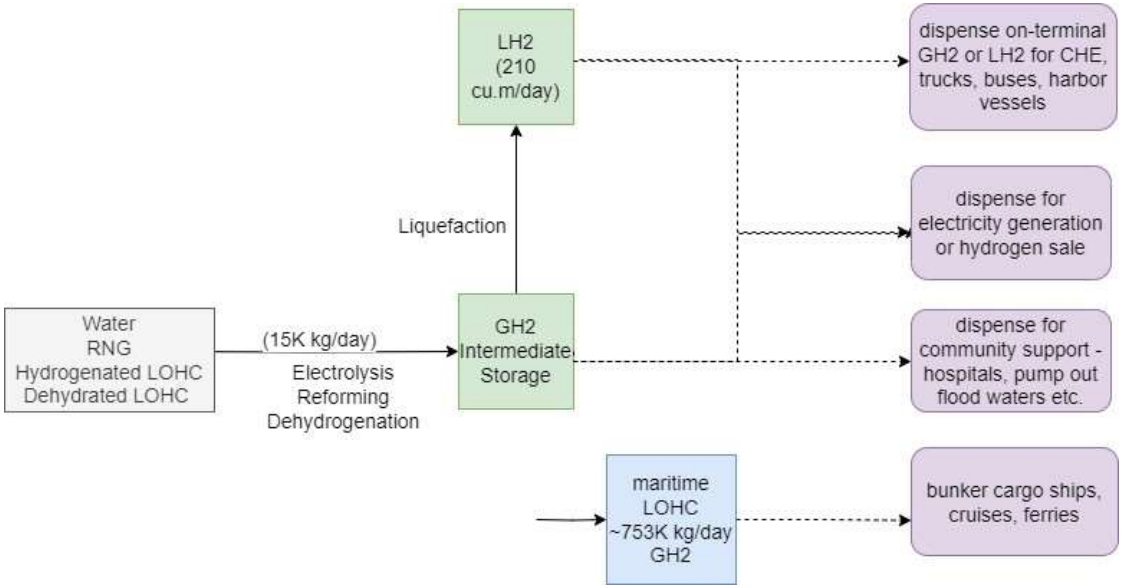
Risk Assessment

- Increases awareness of Probabilistic Risk Assessment (PRA) jobs in hydrogen industry.
- Promotes direct uptake of hydrogen storage risk assessment methodology in the private sector.
- Pools together national lab capabilities from INL, SNL, and PNNL to solve real-world Port problems.

Stakeholder Engagement task of this project is supporting community and stakeholder outreach strategies for novel fuel technologies.

Approach:

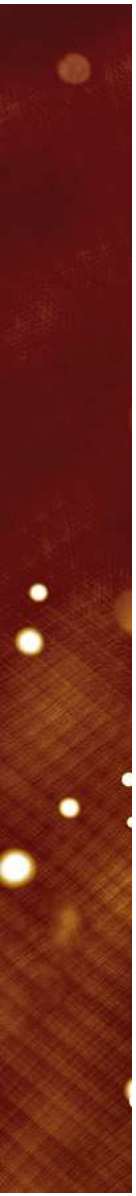
SCL and the Port need hydrogen in a diversity of forms to fulfill their on-terminal, maritime, and societal needs



- Multiple forms of hydrogen and its carriers are needed for Port applications.
- GH2 is best suited for intermediate storage or at the point of fuel cell power generation.
- LH2 is suitable for onsite storage with continuous use.
- Carriers are suitable for long-term/seasonal/bunkering storage and transportation.
- While GH2 and LH2 may be produced and stored onsite, production of other carriers is energy intensive and possibly need external supply.

- **Prior and ongoing work** done through HFTO is heavily leveraged to compare high level hazards of alternative fuels.
- **Major barriers** on the critical path are alleviated through prior work and extensive engagement with the public-facing agencies
- Project is **on target** towards meeting Y2 Q3 milestone.
- **Go/no-go milestone** passed in October 2023. A stakeholder engagement workshop was held towards meeting the criteria.
- **Uniqueness**: risk assessment methodology is scaled up and tailored to the needs of the real-world.

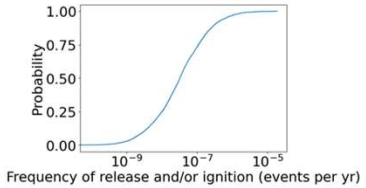
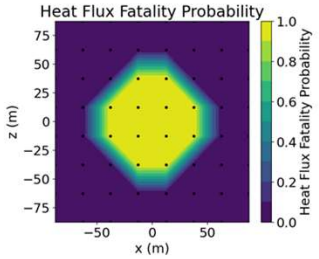
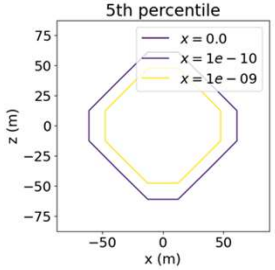
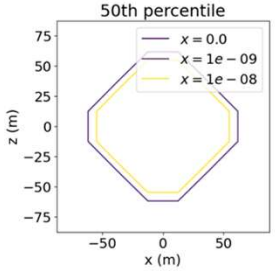
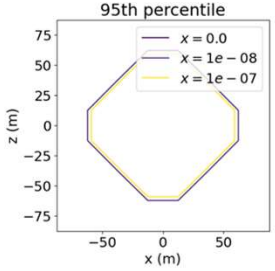
Milestone	End Date
Understand current needs of the Port	12/31/2022
Understand hazards around the Port	3/31/2023
Develop an initial risk model	6/30/2023
Document Y1 findings	9/30/2023
Untertake cybersecurity risk assessment	12/31/2023
Understand future needs of the Port	3/30/2024
Compare hydrogen storage media for maritime needs	6/30/2024
Prepare the final report	9/30/2024



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Accomplishments and Progress:

A single scenario risk was demonstrated, overall risk is the aggregate of all possible scenarios

Frequency of Release and/or Ignition (events per year) (INL SAPHIRE) and Consequence (probability of fatality at each location) (SNL HyRAM+)	Worker Individual Risk (probability of fatality per year)	Worker Societal Risk (fatalities per million people per year)
 (a) Frequency  (b) Consequence Expected number of fatalities: 8	5th percentile  50th percentile  95th percentile 	5^{th}: 0.02 50^{th}: 0.3 95^{th}: 6.4

- In Year 1, a master logic diagram (MLD) was developed identifying potential set of initiating events (IE).
- One of the potential initiating events is a 3/8-inch pipe rupture between a compressor and a GH2 storage tank running at 15000 PSI. The approach to quantify the risk stemming from this IE was illustrated.
- There are multiple pathways originating from this IE resulting in either no consequence, jet fire, or explosion. These were developed using combination of event trees and fault trees.
- The risk arising from the dominant pathway as a combination of frequency and consequence given the IE is illustrated on the left for the pipe rupture scenario on an island populated with 2000 workers at any time of the year.
- Illustratively, there could be around eight fatalities if the hazard manifests. The risk is an uncertain range with a median of 0.3 fatalities per million people per year. There is no established safety goal to benchmark against.
- The overall risk estimation is out of scope but can be determined by aggregating risk taking into consideration exhaustive set of IE from the MLD.

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Accomplishments and Progress:

Compared multiple storage media;GH2, LH2 are suitable for on-terminal usage; alternatives suit the maritime needs

	Gaseous Hydrogen (GH2)	Liquefied Hydrogen (LH2)	Ammonia	Methanol	Formic Acid	Dibenzyl toluene (DBT)
Storage Requirements	Compression	Liquefaction	Refrigeration	Ambient	Ambient	Ambient
Containers	Heavy steel pressure vessels	Thermally insulated cryogenic tank	Carbon or austenitic stainless steel	Carbon or austenitic stainless steel	Composite materials	Stainless steel
Conditions	300-900 bar	−252.8°C	-33°C	Ambient	Ambient	Ambient
Energy Content (wt%)*	100% (120 MJ/kg)	100%	18%	12.5%	4.3%	6.2%
Applications	On-terminal refueling	On-terminal storage	On-terminal storage, maritime fuel	On-terminal storage, maritime fuel	Storage and transportation	Storage and transportation
Common Failure Modes and Hazards	Embrittlement, overpressure, corrosion, leaks	Embrittlement, spill	Stress corrosion cracking, spill, overpressure	Stress corrosion cracking, spill	Environmental stress cracking	Fouling on the tank walls
Controls	Lot of ventilation, composite materials	Thermal insulation	Use an austenitic alloy	Use an austenitic alloy	Use primers	Filter out impurities
Conversion to GH2	-	Evaporation	Cracking	Cracking/ Dehydrogenation	Dehydrogenation	Dehydrogenation
Production	Steam reforming of methane, Electrolysis	Liquefaction of GH2	Haber-Bosch Process	Hydrogenation	Hydrogenation	Hydrogenation
Energy needs (approx.)	55 kWh/kg (electrolysis) 1.7 to 6.4 kWh/kg (compression)	7-13 kWh/kg (liquefaction) 0.37 kWh/kg (vaporizer)	10-12 kWh/kg (production) 0.3 kWh/kg (cracking)	11 kWh/kg (hydrogenation) 2.9 kWh/kg (cracking)	5.3 kWh/kg (hydrogenation) Ambient (dehydrogenation)	12.8 to 16.2 kWh/kg (hydrogenation) 11 kWh/kg (dehydrogenation)
Notes	*the energy obtained assumes 100% concentration of the fuel can be achieved. In reality, the solutions are often diluted for economic reasons.					

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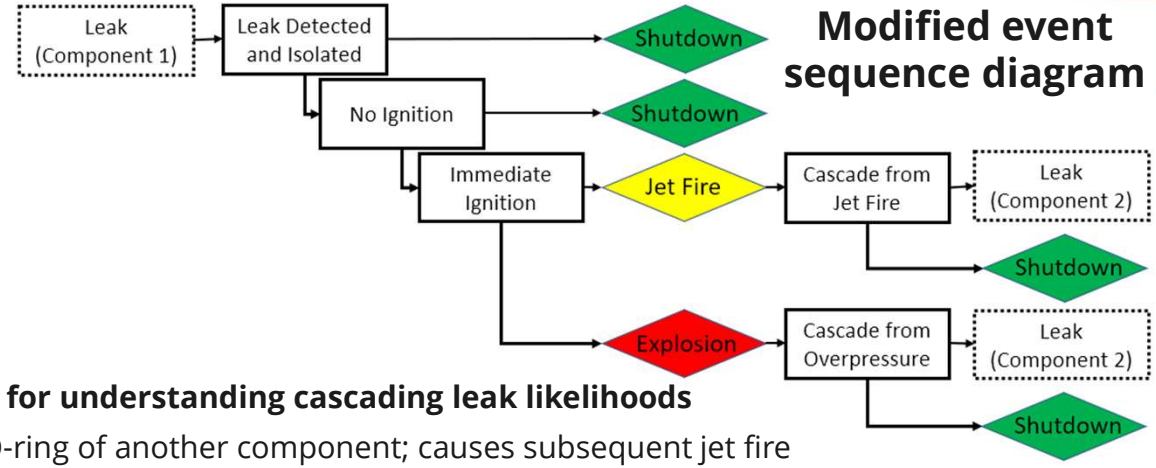
Accomplishments and Progress:

Compared multiple storage media; Alternative fuels are available at varying levels of maturity and hazard levels

Characteristic	Metric	NH3	MeOH	HCOOH	HCOOK	DBT	HFO	MDO	LNG
Inhalation hazard from vapor release	OSHA 8-hr TWA PEL (ppm)	50	200	5	Not listed	Not listed	Not listed	Not listed	1000 (propane)
NFPA Fire rating	Rated 1-5	1	3	2	0	1	2	4	4
Explosion hazard from vapor cloud	Explosive Limits (%)	15%-28%	6%-36%	18%-57%	Not listed	Not listed	0.7% to 5%	0.6% to 7.5%	4% to 15%
Inhalation hazard from spill	Vapor Pressure (mmHg)	775	96	35	Not listed	0.0075	5 (at 100F)	<2	609.5 (at -263F)
Immediate danger to life or health	IDLH (ppm)	300	6000	30	Not listed	Not listed	Not listed	100	Not listed
Carcinogenic		No	No	No	Not listed	No	Yes	Yes	No
Fuel cells for large ocean-going vessels	Year TRL 9 is achieved	~2033	~2029	N/A	N/A	N/A	N/A	N/A	N/A
Combustion engines (2-stroke, 4-stroke)	Year TRL 9 is achieved	~2024, 2025	Ready, 2024	N/A	N/A	N/A	Ready	Ready	Ready
Acute Aquatic Toxicity	Rated 1-5	1	3	3	Not hazardous	Not hazardous	3	2	Not hazardous
pH (acidity)	0-14	12	N/A	3.5	>7.0	Not listed	N/A	N/A	N/A
Reactivity		reacts with oxidizers, acids, halogens, and salts of heavy metals	reacts with strong oxidizers, mineral acids, and reactive metals	reacts with oxidizing agents, strong inorganic and organic bases, and chemically active metals	None	None	Explosive when vapor mixed with air. Reacts with strong oxidizing agents	Reacts with strong acids and oxidizing agents	Reacts with oxidizing agents
Pros		Low flammability	Low toxicity in the event of a vapor release	Low toxicity in the event of a spill	Low toxicity and flammability	Low flammability	High volumetric energy density	High volumetric energy density	High volumetric energy density
Cons		High toxicity in the event of a spill	High flammability and lower explosive limit	High toxicity in the event of a vapor release	Low volumetric density	High energy consumption for dehydrogenation	Emissions	Emissions	Emissions
Comments		For vapor pressure, methanol and formic acid are assumed to be stored at ambient temperature, and ammonia at -28F. Specific hazards manifest depending on conditions - geometry, release rate, chemical characteristics. *85% concentration formic acid has been achieved, but the properties in the table above are based for 90% concentration. For potassium formate, 70wt% solution has been achieved. N/A – Not available, NH3 – Ammonia, MeOH – Methanol, HCOOH – Formic acid, HCOOK – Potassium Formate, DBT – Dibenzyl toluene, HFO – Heavy Fuel Oil, MDO – Marine Diesel Oil, LNG – Liquefied Natural Gas							

PROGRESS: CASCADING FAILURES IN HYDROGEN STORAGE

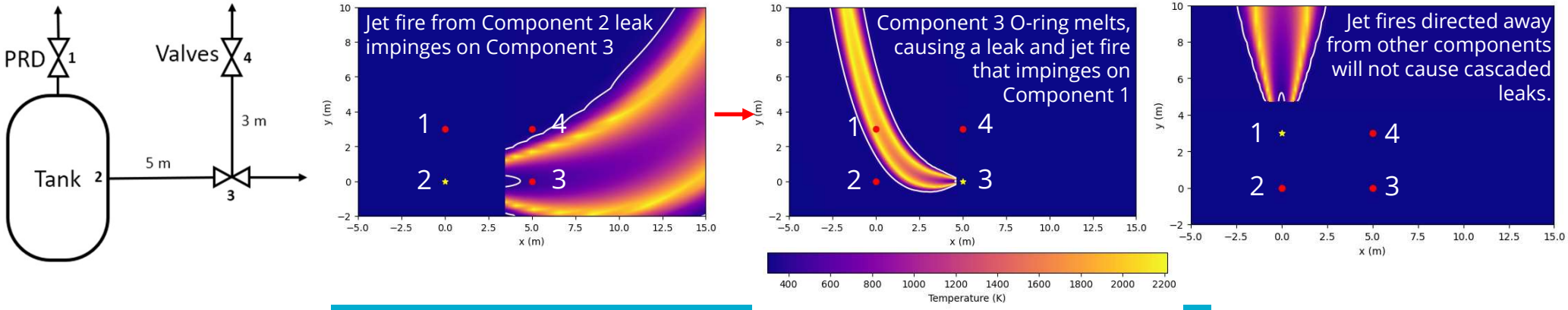
- Historical examples of cascading accidental releases in hydrogen storage systems
  - Air Products hydrogen trailer (Santa Clara, 2019)
  - N2 ammonia plant (Porsgrunn, Norway, 1985)



Modified event sequence diagram

Rudimentary case studies for understanding cascading leak likelihoods

Example: impinging jet fire melts O-ring of another component; causes subsequent jet fire



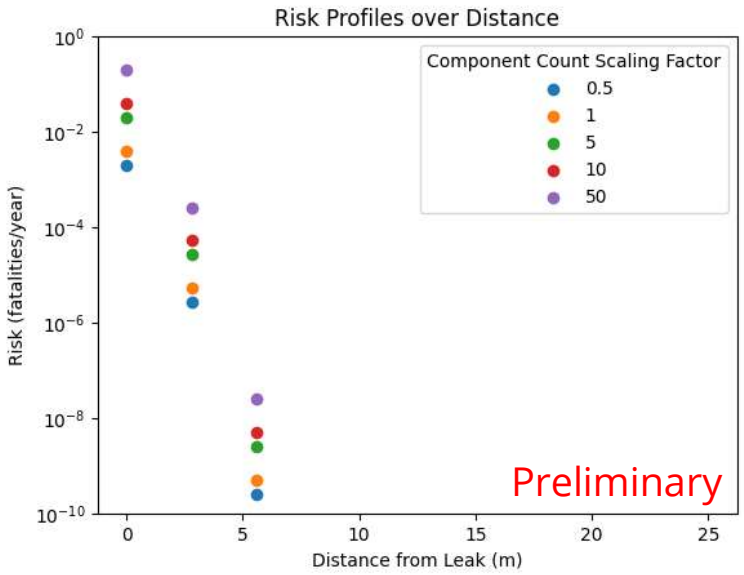
Increasing understanding of cascading failure mechanisms and probabilities can facilitate system design improvement.

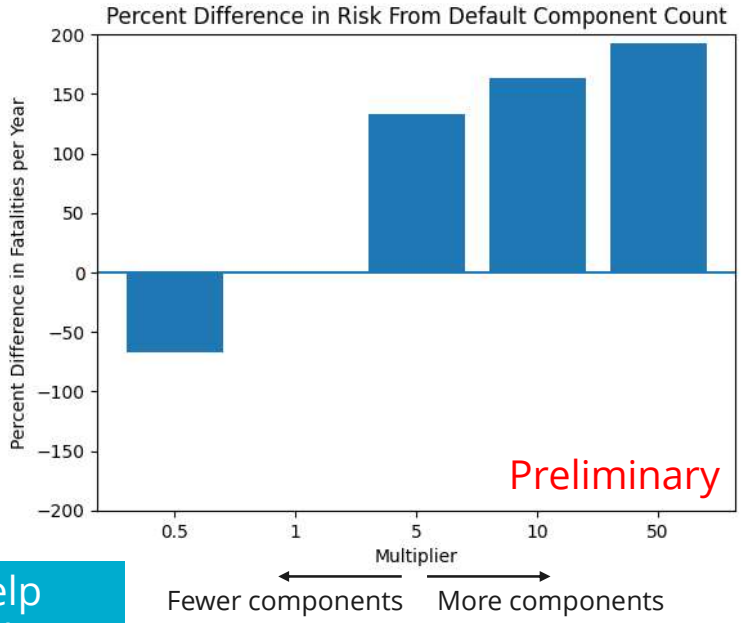
Future cascading failure work: finalize case studies and scenarios

PROGRESS: RISK-INFORMED LARGE SCALE GH_2 STORAGE THRESHOLD IDENTIFICATION USING COMPONENT COUNTS

- Gaseous hydrogen is likely to be stored modularly (in **more** cylinders instead of **bigger** cylinders)
- More modules → more components → higher leak frequencies for overall system → higher risk

Component	Base Case
Compressor	2
Vessel	3
Valve	37
Instrument	32
Joint	45
Pipe	100
Heat Exchanger	2





Quantitative risk assessment can help determine if a GH_2 storage threshold is needed in safety codes and standards.

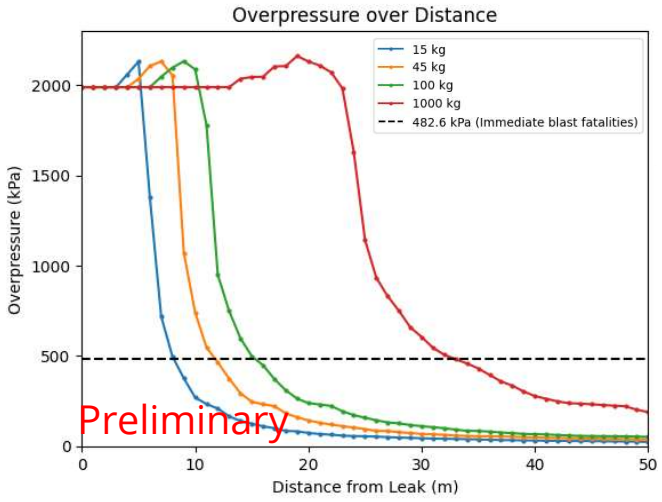
PROGRESS: CONSEQUENCE-INFORMED LARGE-SCALE LH_2 STORAGE THRESHOLD

Current stored fuel quantity thresholds are not risk or consequence-informed.

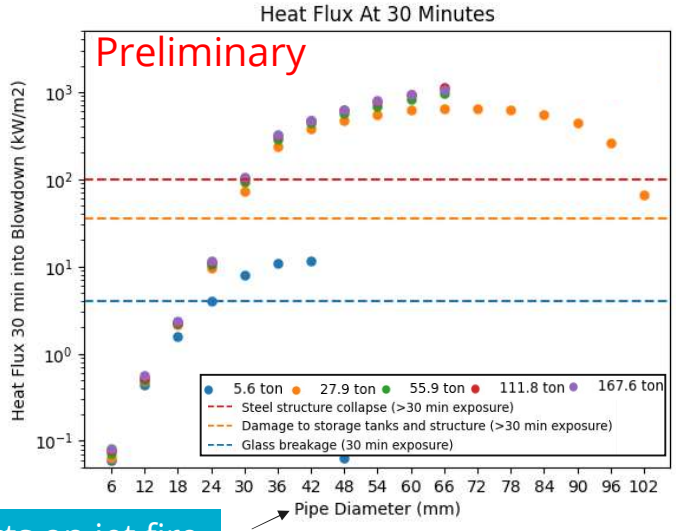
- NFPA 2 (2023): 75,000 gal limit for LH_2 // NFPA 59A (2023): 1,056,000 gal limit for LNG

Is there a hydrogen storage quantity threshold that should be recommended? What should it be based on?

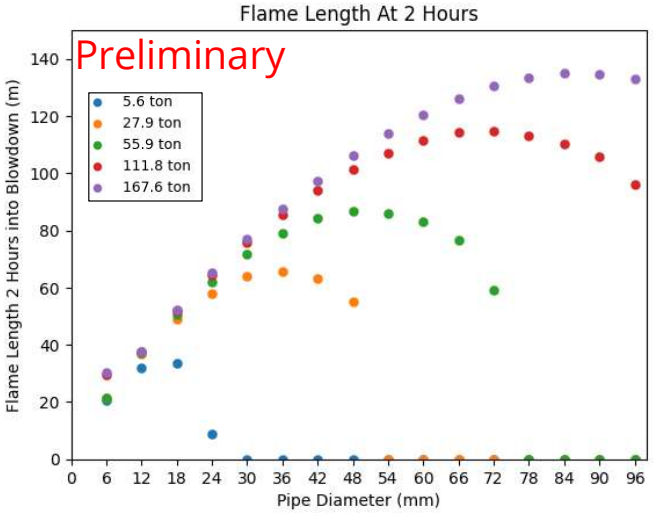
Explosion overpressure levels show distances to harm to people



Jet fire heat flux levels show extent of damage to infrastructure



Jet fire flame length show reach of damage to infrastructure



Understanding stored fuel quantity effects on jet fire and explosion damage can inform regulations, codes, and standards quantity thresholds or setback distances.

Pipe diameter is typically, but not necessarily, somewhat correlated with storage capacity.

Future large-scale storage work: continue to explore options to define a storage threshold and engage with regulatory committees such as NFPA 59A and NFPA 2

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Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- This project "Large-Scale Hydrogen Storage - Risk Assessment Seattle City Light and Port of Seattle" was not reviewed at a previous AMR

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Collaboration and Coordination:
Stakeholder Engagement Far and Wide

- FFRDC Partners
  - Sandia National Laboratories
- Cost Sharing Industry Partners
  - Seattle City Light, Port of Seattle
- Advisory Board
  - Industry
  - Academia (WSU, Univ. of Maryland, Leibniz Univ.)
  - Agencies (Port of Portland, Long Beach, Tacoma)
  - Consortia (CHARGE)
  - Alliances (NWSP: Northwest Seaport Alliance)
- Codes and Standards Committees
  - ASME Hydrogen Steering Committee
- ASME Hydrogen Risk and Reliability Analysis Conference (HyRRAC)
  - ASME, PNNL, UMD

City of Seattle Utility Services

Port of Seattle

Sandia National Laboratories

bp

Air Liquide

Par Pacific

KINDER MORGAN

STARS Technology Corporation

1898 & CO.

OCO CHEM

CH2ARGE

THE NORTHWEST SEAPORT ALLIANCE SEATTLE + TACOMA

Structural Integrity Associates, Inc.

MCDERMOTT

ASME

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DEIA/Community Benefits Plans and Activities:
PNNL and the Port completed an outreach with a community-facing agency

- **The Port Community Action Team (PCAT)** is a Port-facilitated advisory group consisting of a diverse group of Duwamish Valley community members who interface with Port staff and advocate for the surrounding community.
  - The Duwamish Valley experiences some of the most significant air quality issues in the city of Seattle.
  - These near-Port neighborhoods are largely linguistically isolated, low income, communities of color, with many people in vulnerable age categories.
- **We met with PCAT** in partnership with Port engagement staff to open the conversation about current and future maritime fuels, focusing on the concept of direct vs lifecycle emissions and related justice issues.
  - Initial feedback from PCAT members showed interest in deeper understanding of a variety of fuel options and encouragement for Port staff to participate in visioning exercises from community perspectives.
  - A follow-up survey requesting both structured and unstructured responses will be distributed, and PCAT members were encouraged to directly contact project staff for additional dialogue.

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Remaining Challenges and Barriers:
Uncertainties in use cases, energy source portfolio, and storage footprint

- Challenge: Determining operational risks related to various SCL and Port use cases.
  - Barrier: Uncertainty in timing and duration of future use case scenarios.
  - Proposed solution: Expert judgment and extensive stakeholder engagement.

- Challenge: Determining the storage footprint and associated bunkering challenges.
  - Barrier: Uncertainty in future fuel energy source portfolio.
  - Proposed solution: Assume low, medium, high use case scenarios proportional to the current portfolio.

- Challenge: Large-scale storage requires assessing risks associated with cascading failures and gaps in safety codes and standards.
  - Barrier: The number of storage tanks required, and their hydrogen carrier content are unknown.
  - Proposed solution: Apply expert judgment and appropriate assumptions

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Proposed Future Work:
Future needs risk assessment and the final report

- The rest of FY2024 Q3 and Q4 will focus on operational risks and the final report:
  - Footprint for hydrogen carriers
  - Bunkering hazards
  - Capture feedback from most recent workshop on community engagement and conceptualize potential next steps for the Port
  - Comprehensive report detailing the Port requirements, hazards around the Port, risk assessment methodology and associated results, future needs and associated operational risks, and stakeholder engagement efforts.

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Summary:

Large-scale hydrogen storage risk assessment methodology is impactful to Ports, Utilities, and HFTO

Goal	Help Utilities and Ports in undertaking risk assessments that yield public safety risk metrics and in effective stakeholder engagement
Impacts	Decarbonization, risk assessment, and stakeholder engagement
Approach	Applies a series of risk assessment techniques from ISO 31010 towards understanding hydrogen plant systems, their failure modes, and safety risks.
Accomplishments	Compared the hazard characteristics and maturity of various hydrogen carriers, completed cybersecurity risk assessment, organized workshops with community-facing agencies.
Collaboration	Port of Seattle, Seattle City Light, Sandia National Laboratories, Advisory Board, Code and Standards Committees.
Challenges	Uncertainties in use cases, energy source portfolio, and storage footprint
Future Work	Future needs risk assessment, comprehensive technical report