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Risk Assessments of Design and Refueling for Hydrogen Locomotive and Tender

Project ID: SCS033

DOE Project Award #: NL0038749

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Project Team:
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DOE Hydrogen Program

2023 Annual Merit Review and Peer Evaluation Meeting

June 5-8, 2023

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

SAND2023-02137PE

Project Goal

Using qualitative and quantitative risk assessments to:

- Enable Wabtec's near term deployment of hydrogen-powered locomotives
- Inform the applicable regulatory community about developments, needs, and identified gaps in this hydrogen-powered rail transportation sector that will need to be addressed in the near term

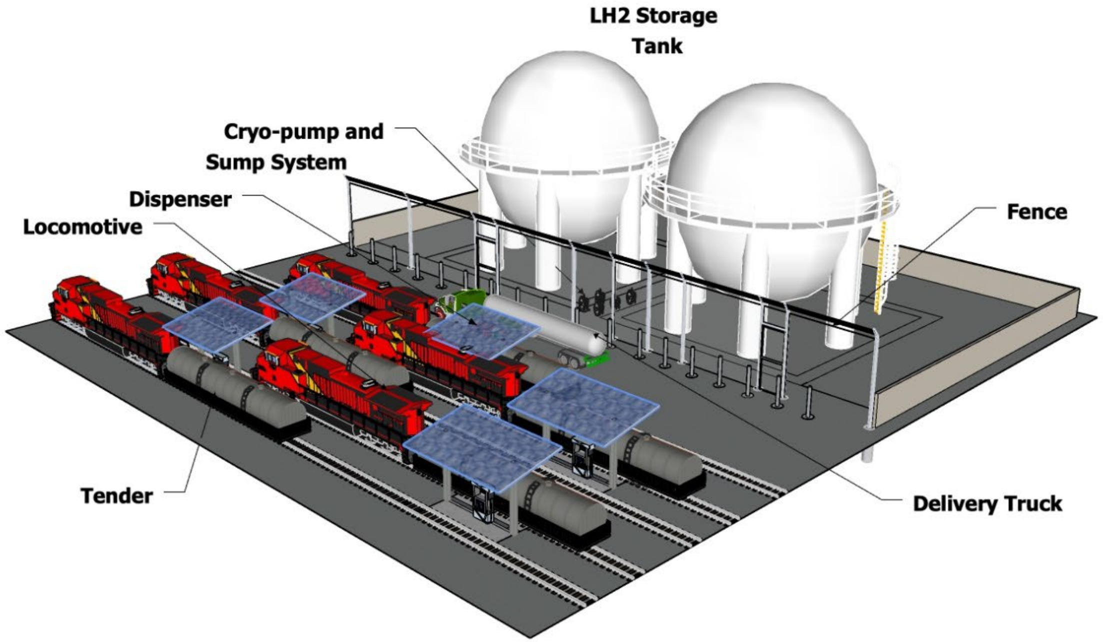


Image: Ehrhart, Brian, Gabriela Bran Anleu, Jamal Mohmand, Austin Baird, and Leonard Klebanoff. *Refueling Infrastructure Scoping and Feasibility Assessment for Hydrogen Rail Applications*. Sandia National Laboratories SAND2021-12851, 2021.

Overview

Timeline

- Project Start Date: 02/01/2022
- Planned Project End Date: 12/31/2023

Budget

- Total Project Budget: $750,000
  - DOE Share: $525,000
  - Cost Share: $225,000
    - Funds-In: $75,000
    - In-Kind: $150,000
- Funds Spent To-Date:
  - DOE Share: $204,985
  - Cost Share: $20,827
  - As of: 3/31/2023

Barriers

- Lack of requirements for new applications
- Lack of scientific bases for defining requirements
- Lack of widespread dissemination of safety-related information resources

Partners

- Project Lead: Sandia National Laboratories
  - Brian Ehrhart (PI, Sandia National Laboratories)
- Partner Organization: Wabtec
  - Chris Homison (PI, Wabtec)

Relevance/Potential Impact

- SCS Goal: Facilitating the creation, adoption, and harmonization of regulations, codes, and standards (RCS) for hydrogen and fuel cell technologies
  - Through analyzing hydrogen-powered locomotive failures and their associated risks, this project can help inform hydrogen-rail specific codes and regulations that benefit this new and emerging area.

- SCS Goal: Conducting research to generate the valid scientific bases needed to define requirements in developing RCS
  - Conducting these different risk analysis’ will shed light on areas that need further study to conduct more accurate and detailed risk assessments which can feed into the development of new regulations, codes, and standards.

- SCS Goal: Performing RD&D to inform deployment and enable compliance with RCS
  - The analysis will directly impact ongoing efforts at Wabtec and their design of various hydrogen-powered locomotives. By doing these types of studies in the design stage rather than retrospectively Wabtec will be able to risk-inform their designs and ensure their compliance with both current RCS as well as help identify areas of potential improvement.

- SCS Goal: Developing and enabling widespread dissemination of safety-related information resources and lessons learned
  - The RCS gap analysis in conjunction with the risk analysis will be vital to the adoption of these new technologies. It will help designers know which current requirements are aligned for hydrogen applications and which regulations may need to be modified to account for hydrogen specific impacts.

Approach and Milestones

- Perform an failure mode and effects analysis (FMEA) or hazard and operability (HAZOP) study to generate a qualitative risk ranking of hydrogen release scenarios of hydrogen-powered locomotives.
  - From the FMEA/HAZOP study analyze specific high risk scenarios to further analyze their potential risk impact on humans. This may include a hydrogen release analysis, failure rate determination, or other analysis.
- Perform a Fault Tree and Event Tree Analysis to quantify the risk of hydrogen refueling and transfer scenarios. The baseline fault tree developed in HyRAM+ will be used and then further expanded upon to include system specific failures and impacts.
- Review Federal Railroad Administration (FRA), Pipeline and Hazardous Materials Safety Administration (PHMSA), and other codes and standards developed for the use of diesel, gasoline, or natural gas as a basis. Identify requirements that hydrogen-locomotives may need to follow and any requirements that may need expansion, adaptation, and clarification in order to support hydrogen-powered rail.

Brian D. Ehrhart, Cianan Sims, Ethan S. Hecht, Benjamin B. Schroeder, Alice B. Muna, Katrina M. Groth, John T. Reynolds, Myra L. Blaylock, Erin Carrier, Isaac W. Ekoto, and Gregory W. Walkup. HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models), Version 4.0. Sandia National Laboratories (October 6, 2021); software available at hyram.sandia.gov.

Approach and Milestones

Projected Completion Date	Milestone Description	Percent Complete
6/30/2022	Identification of at least 3 failure modes each for at least 5 components for both the on-board locomotive and tender	100%
6/30/2022	Outreach to and obtain feedback on approach from AAR Locomotive Committee and Federal Railroad Administration through at least 1 meeting with each	100%
12/31/2022	Consequence modeling of both thermal and overpressure effects from on-board leaks for locomotive and tender car for at least 5 different leak scenarios	100%
3/31/2023	Estimation of likelihood/frequency of fuel transfer leaks for at least 5 components for fuel transfers from the refueling station to the tender car (LH2) and from the tender car to the locomotive (GH2) and directly from the refueling station to the locomotive (GH2) for at least 3 leak sizes informed by at least 3 independent sources	100%
3/31/2023	Consequence modeling of thermal and overpressure effects for fuel transfers from the refueling station to the tender car (LH2) and from the tender car to the locomotive (GH2) and directly from the refueling station to the locomotive (GH2) for at least 3 different leak scenarios	100%
6/30/23	Present work to a minimum of 2 minority serving institutions or similar educational groups	0%
6/30/2023	Outreach to and obtain feedback on approach from AAR Locomotive Committee and Federal Railroad Administration through at least 1 meeting with each	0%
9/30/2023	Complete gap analysis of current FRA and PHMSA codes/standards with respect to applicability to hydrogen rail normal and refueling operations.	0%
12/31/2023	Final report for risk assessments for at least 5 scenarios for on-board components for a locomotive and tender car as well as at least 3 scenarios for fuel transfers from refueling station and tender and at least 3 risk reduction strategies for both	0%

Progress: On-Board Component Failure Modes and Effects Reviewed

- Initial failure mode and effects analysis complete
  - Assessed **on-board component** failures
  - Qualitative analysis categorizing likelihood and outcome to assess risk
  - Included fuel cell and internal combustion engine designs, both gaseous and liquid hydrogen (~150 components)
- Highest-risk components identified

Frequency Classes

Eliminated / Incredible	Improbable	Remote	Occasional, Probable, Frequent	*Frequency*
f < 1E-6	1E-6 < f < 1E-4	1E-4 < f < 1E-2	f > 1E-2	*Frequency Bounds (per year)*
1	2	3	4	*Numerical Level*

Leak Outcome Classes

Component Size	*Failure Mode*	*Pressure (bar)*	*Rating*	*Numerical Level*
Small or Large	All	Low, <8	Low	1
Small or Large	All	Medium, 8-20	Medium	2
Small	All	High, 350-700	High	3
Large	All Other	High, 350-700	High	3
Large	Rupture	High, 350-700	Massive	4

1	2	3	4
2	4	6	8
3	6	9	12
3	6	9	12
4	8	12	16

Number of Scenarios in Each Risk Category

	Eliminated/Incredible (1)		Improbable (2)		Remote (3)		Occasional, Probable, Frequent (4)	
	Pre-Mit.	Post-Mit.	Pre-Mit.	Post-Mit.	Pre-Mit.	Post-Mit.	Pre-Mit.	Post-Mit.
Low (1)	0	0	28	39	16	18	0	0
Medium (2)	0	0	11	19	2	8	0	0
High (3)	0	0	42	23	15	7	0	0
Massive (4)	1	1	2	2	0	0	0	0

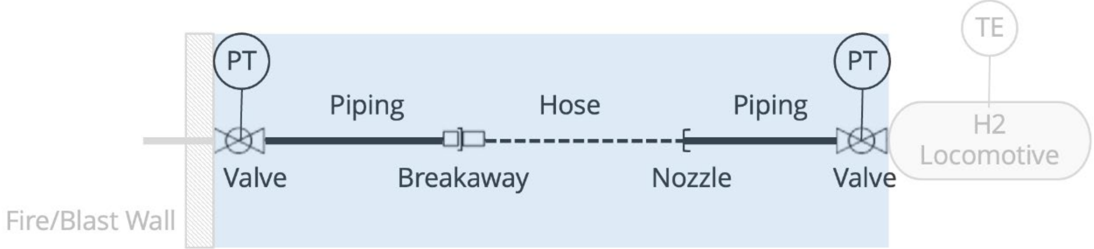
Preliminary

- Impact of example mitigation illustrated
  - Automatic shutoff valve can reduce severity of some leaks
- Some scenarios move to lower-risk categories
- Other preventions/mitigations will have different effects

Qualitative risk rankings can help identify design or operational changes to improve safety for hydrogen rail

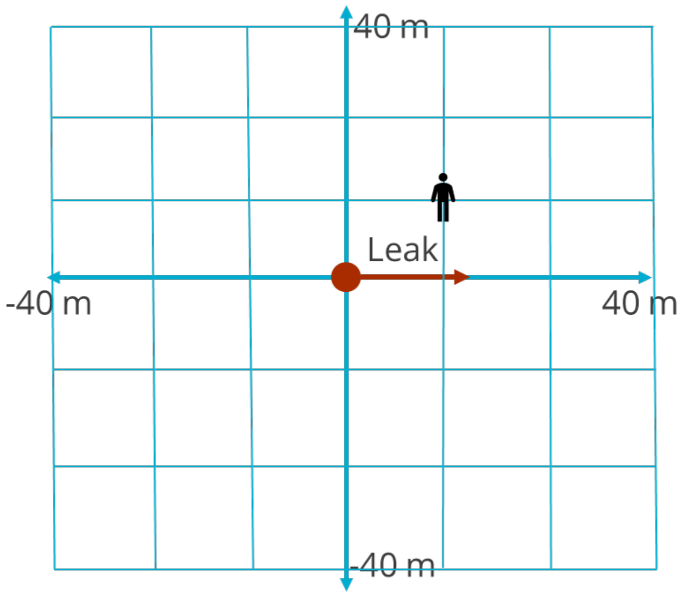
Progress: Refueling Risk Assessment Started

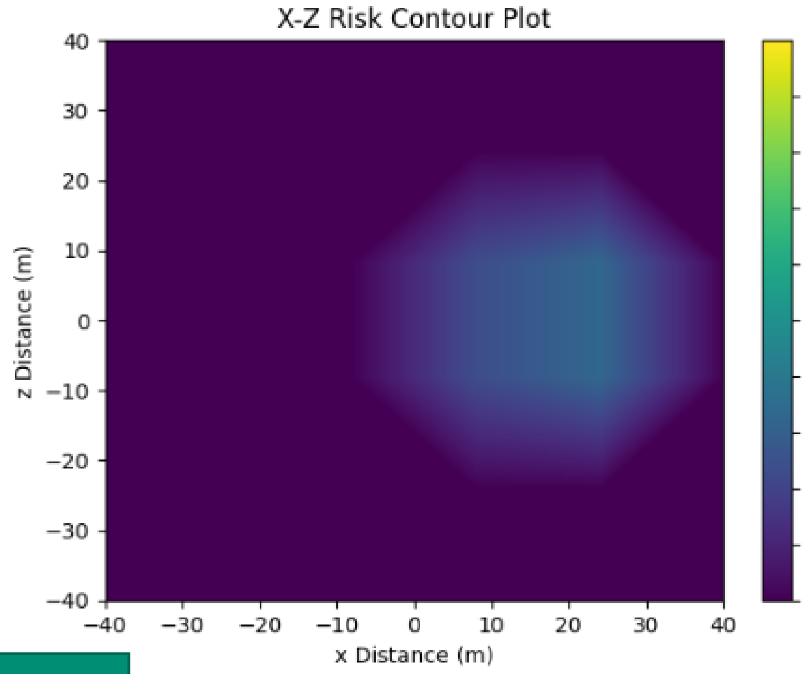
- Quantitative **risk analysis** of failures at the **rail refueling dispenser** started
  - Initial results for dispenser components only
  - Gaseous hydrogen refueling at 350 bar
- Risk calculated at various locations to consider risk to operator, other staff on-site, off-site



Component	Valves	Piping (m)	Hoses	Instruments	Joints
Count / length (m)	2	10	1	2	8

- Different components and outcomes contribute to risk differently
- Result to be compared to future calculations to **assess preventative/mitigative measures**
  - Also **considering uncertainty/variability** in risk calculations





Preliminary

Quantitative risk of heavy-duty refueling can inform future safety requirements

Progress: Rail Specific Regulations, Codes, and Standards Identified

- Locomotives and tender cars subject to Department of Transportation **Federal Railroad Administration (FRA) regulations**
- Refueling facilities likely subject to **Hydrogen Technologies Code (NFPA 2)**
- Staff currently participating in **American Public Transportation Association (APTA) working group** for battery and hydrogen safety white paper for passenger rail

Understanding existing requirements can help to incorporate risk research into informing future requirements

Images:
https://twitter.com/USDOTFRA
https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2
https://www.apta.com/

Responses to Previous Year Reviewers' Comments

This project has not been reviewed previously at an AMR

Collaboration and Coordination

- Wabtec
  - CRADA participant and Cost Share partner
  - Industry
  - Provide design information, analysis feedback, and general guidance of project
- Wabtec is vital to the success of this project, they are in the process of designing both internal combustion and fuel cell hydrogen-powered locomotives. They are providing the project team vital information on the design of the system to be analyzed to ensure the safety of their design. Sandia National Laboratories and Wabtec teams meet on a bi-weekly basis to discuss progress and exchange information and any updates for their various designs.

Remaining Challenges and Barriers

- Limited availability for hydrogen-specific component failure rates for rail-relevant conditions
  - High flow rates for refueling, high-shock/vibration on-board
- Determining the applicability of similar analyses conducted for diesel, natural gas, and other fuel systems to hydrogen counterparts can make direct comparisons difficult
  - Assessing risk for hydrogen system only may incorrectly imply an increase in risk over status quo
- Common-cause or cascading failures for the hydrogen-powered locomotives can be difficult to assess systematically
  - System interactions of novel designs and how those might introduce unexpected failure states

Proposed Future Work

- Extend failure modes and effects analysis for hydrogen components on-board locomotive and tender
  - Identify and assess other prevention or mitigation measures to show effect on scenario classification
  - Assess high-risk components in more detail, consider possible design changes to lower risk
- Quantify risk for different scenario sets of hydrogen rail refueling
  - Extend analysis to include liquid hydrogen refueling
  - Perform multiple calculations for different sensitivity cases to quantify variability in results
  - Assess different prevention and mitigation measures, such as the use of barriers, personal protective equipment
- Perform a gap analysis of regulatory codes and standards
  - Review FRA and PHMSA regulations for rail developed for the use of diesel, gasoline, or natural gas as a basis
  - Review current requirements for light-duty vehicle refueling in NFPA 2
  - Identify possible requirements that hydrogen-powered locomotives and tender may need to follow

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:**
  - Enable heavy-duty hydrogen-powered locomotives through applied risk assessments
- **Approach:**
  - Perform qualitative and quantitative risk assessments to help inform the design and quantify the risks associated with hydrogen-powered locomotives
  - Review existing regulations, codes, and standards that could apply to hydrogen-powered locomotives to better inform future requirements
- **Progress:**
  - Initial failure mode and effects analysis complete for hydrogen components on-board locomotive
  - Initial quantitative risk assessment done for a single case of rail refueling of gaseous hydrogen
  - Existing regulations, codes, and standards identified for review
- **Future Work:**
  - Extend assessment of on-board components to better compare locomotive and tender components and identify improvements
  - Extend refueling risk assessment to consider both variability of risk and effect of possible safety improvements
  - Perform gap analysis of regulatory codes and standards
  - Prepare final report