Component Failure R&D

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DOE Hydrogen and Fuel Cells Program
2020 Annual Merit Review and Peer Evaluation Meeting

Project ID # SCS001

Overview

Timeline and Budget

- Project start date: 2019
- FY19 DOE funding: $150k
- FY20 planned DOE funding: $400k
- Total DOE funds received to date: $550k

Barriers

A. Safety Data and Information: Limited Access and Availability

F. Enabling National and International Markets Requires Consistent RCS

G. Insufficient Technical Data to Revise Standards

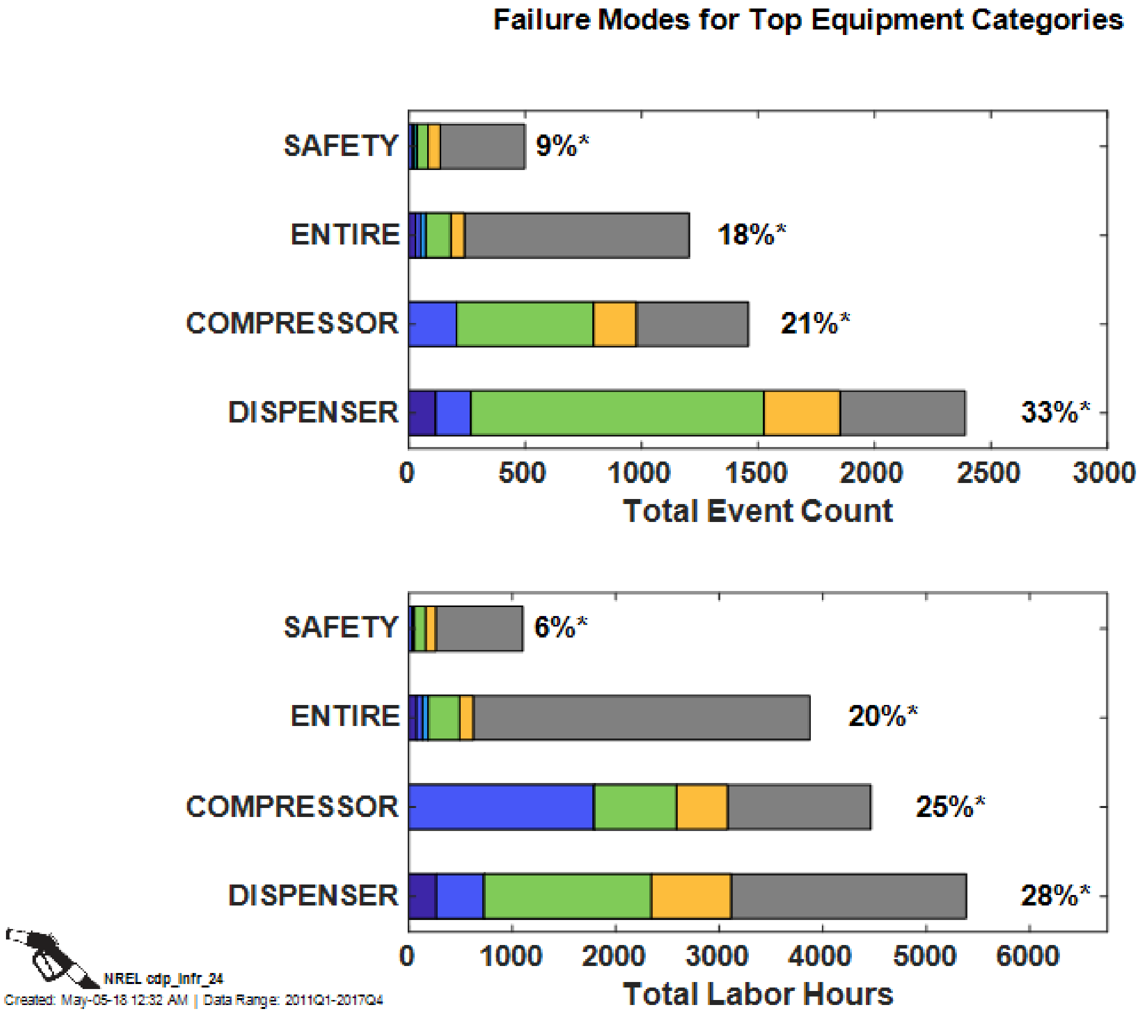
K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development

Partners

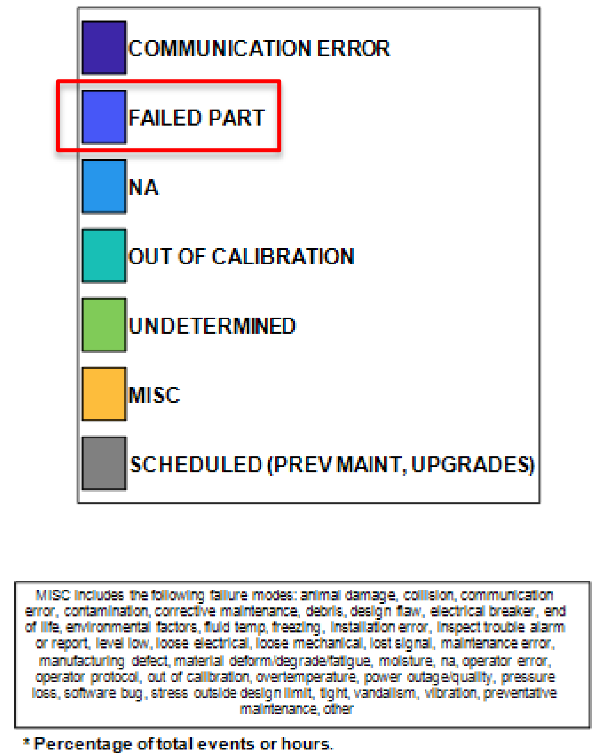
- University of Maryland
- First Element

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

Relevance: Failing Components Disrupt Stations



Failed parts lead to significant downtime and costs



Find all hydrogen infrastructure composite data products (CPD) from NREL [online](), including the figure above (CDP INFR 24).

Relevance: Failed Components Increase Risk

We can detect leaking components, but:

- What is the mass flow rate of this leak?
- What is the hazard that is created?

A thermocouple that would not hold pressure during a leak check is found to be leaking after an application of soap and water

Relevance: Can We Estimate the Risk from Failing Components?

- Risk is a combination of both frequency and severity for the different failure and hazard scenarios of interest
- There is a general understanding of how often components fail and the ways in which they fail in hydrogen service
- There is very little *quantitative* information about how much hazard is present when a hydrogen leak is detected

- Can we quantify the rate that hydrogen is emitted from components that have failed in hydrogen service?
- Can we use that flow rate data to inform risk models and calculations?
- If so, we can provide those data to industry and the codes and standards communities to inform their decisions

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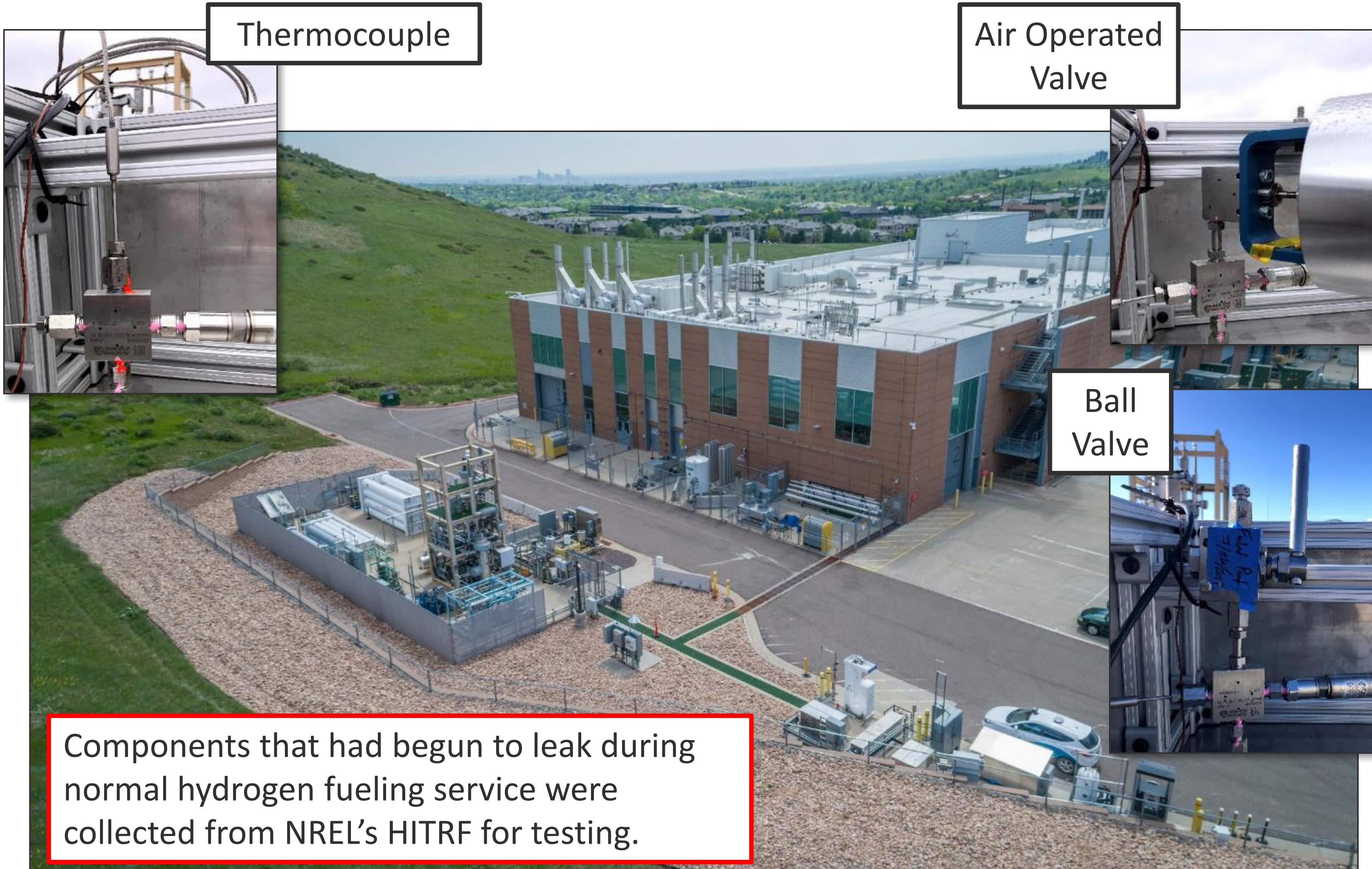
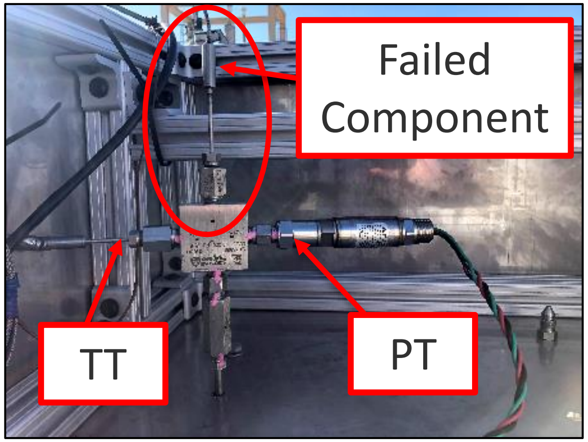
Approach: Components from NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF)



Components that had begun to leak during normal hydrogen fueling service were collected from NREL's HITRF for testing.

Approach: Developing a System to Safely Quantify Leakage from Real Failed Components



- The Leak Rate Quantification Apparatus (LRQA) was designed to safely quantify leak rates from failed components
- The LRQA is capable of testing with hydrogen at up to 13,000 psi
- Hazards are limited by:
  - The pressure vessel is isolated during tests, containing up to 50 gH_2 at full pressure.
  - The device under test (DUT) is placed at the top of a tower at the same height as other vents (10 ft) to limit gas accumulation near operators.
  - The DUT is placed in an open-topped enclosure that shields personnel from self-ignited jet flames.
- Pressure and temperature are recorded upstream of the DUT and at the storage vessel

Approach: Correlating Mass Loss to an Equivalent Nozzle Throat Diameter

- Recording the pressure and temperature in the vessel allows us to correlate leaks to an equivalent orifice throat diameter
  - Calculate the mass in the pressure vessel at each time step using the REFPROP product from NIST for density calculations

$$\dot{m} = \frac{\Delta\rho(fluid, T, p)}{\Delta t} * \mathrm{V}_{\mathrm{system}}$$

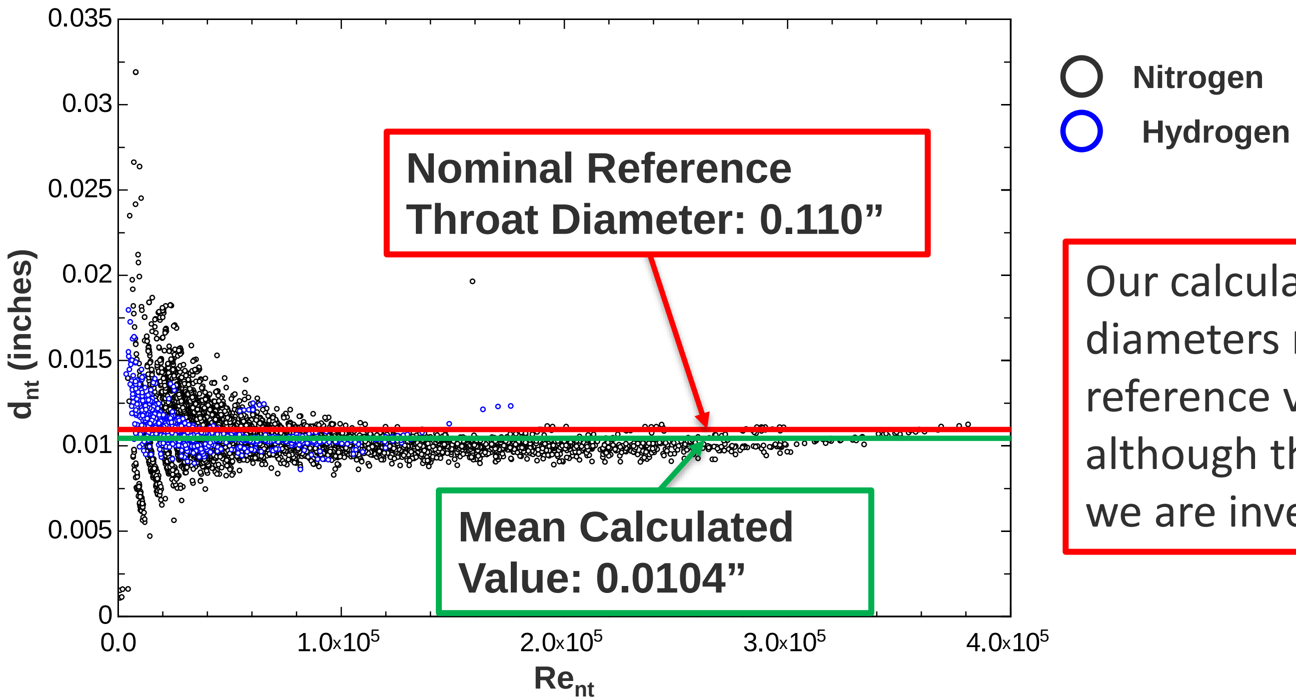
  - Mass flow is related to an equivalent critical nozzle throat diameter using calculations from ISO 9300

$$\dot{m} = \frac{\pi}{4}\boldsymbol{d}_{\boldsymbol{nt}}^{2} * C_d * C^* * p_0 * \left(\frac{R}{M_{fluid}} * T_0\right)^{-0.5}$$

Estimated orifice diameters can be used to predict leak rates at any pressure and temperature condition

Approach: System Validation with a Calibrated Orifice

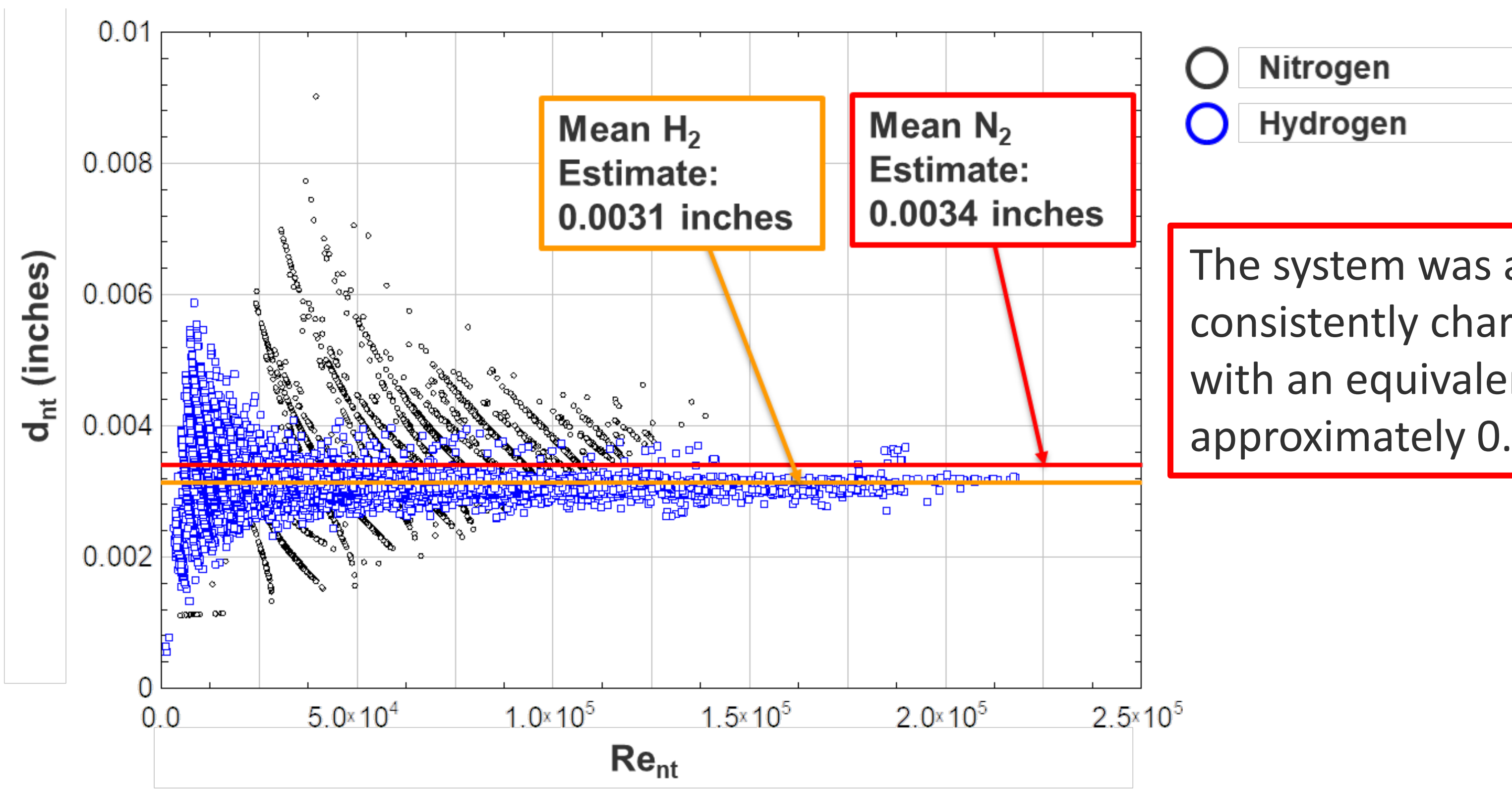
- Installed a NIST traceable calibrated orifice with throat diameter Ø=0.011 inches in place of a failed component
- Tested the calibrated orifice with N_2 and H_2
  - Established the accuracy of flow calculations from pressure and temperature measurements



Our calculated nozzle throat diameters matched the reference value within 10%, although there is a bias that we are investigating

Accomplishments and Progress: Testing Real Components

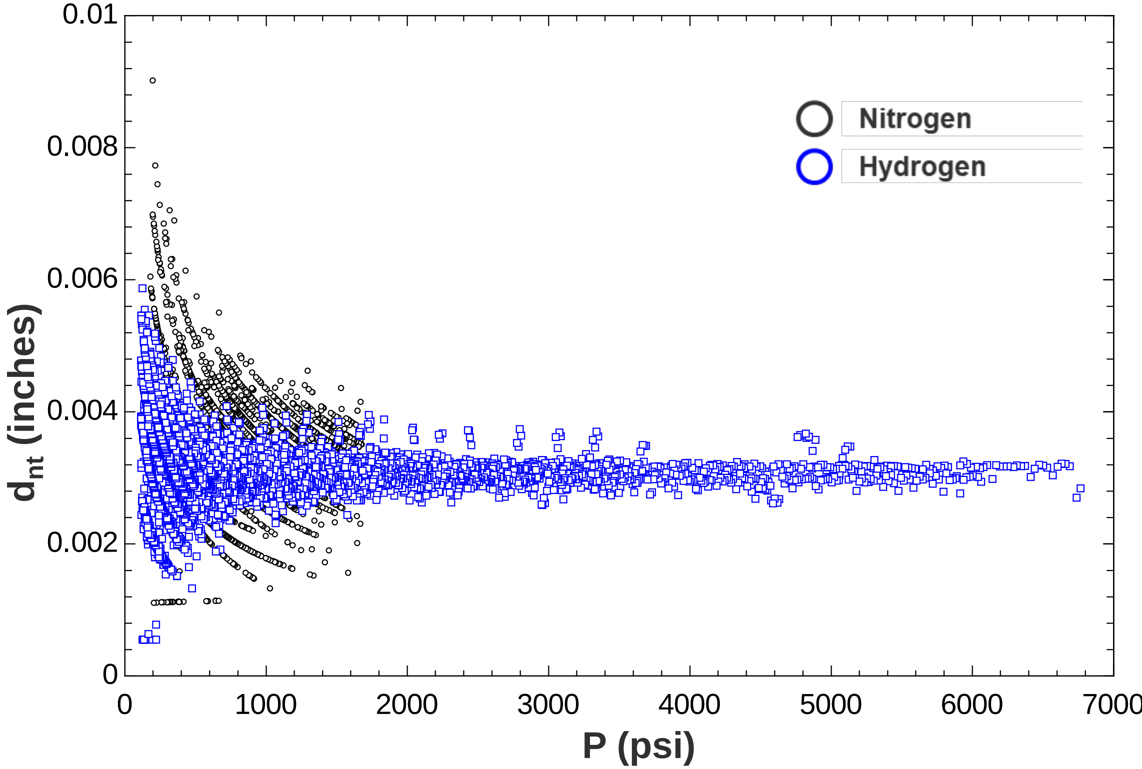
- Demonstrated the ability to characterize leakage through failed components using both hydrogen and nitrogen
  - The calculation of an equivalent orifice diameter used an assumed constant value of $C_d = 0.9$
- Data from characterizing the leakage through an air operated valve (AOV) is illustrated below



The system was able to consistently characterize a leak with an equivalent diameter of approximately 0.003”

Accomplishments and Progress: Testing Real Components

- When plotted versus pressure rather than Reynolds Number, the nitrogen and hydrogen data agree more closely
- This indicates that our primary source of uncertainty is the pressure transmitter, which is ranged 0-15,000 psi with an uncertainty of ±0.1% full scale



The uncertainty in d_{nt} falls significantly for pressures >3,000 psi, which is the primary area of interest for hydrogen fueling applications

Approach: Improving Risk Models with this Data

- Provide data to validate assumptions and input parameters for quantitative risk analysis (QRA) models
- Data and lessons learned will be distributed to the Hydrogen Codes and Standards Community
  - These data could inform standards related to e.g. setback distances for hydrogen stations

Risk models that drive standards can be improved by incorporating data that is specific to hydrogen fueling applications

NREL Characterizes the Leak Rate from Failed Components → QRA Specialists Incorporate these Data into their Models → Stakeholders Use Improved Models to Revise Codes & Standards

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

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- Project was not reviewed last year.

Collaboration and Coordination

- University of Maryland (UMD)
  - Relationship: Sub (Subcontract formally implemented May 4, 2020)
  - University
  - Outside of the DOE Hydrogen and Fuel Cells Program
  - Objective: Provide a **science & engineering** basis for assessing safety (risk) of H_2 systems and **facilitate use of that information** for revising RCS for hydrogen systems.
    - Bring differentiating expertise in QRA, system safety, data analysis, and reliability to connect complementary national lab strengths
    - Develop state-of-the-art QRA tools, methods, & results to support evidence-based RCS development **for LH2 on site storage**
    - We seek to extend the state of the art in risk-mitigation measures to reduce barriers to deployment of LH2 storage technologies.
      - Advanced reliability methods like Prognosis and Health Management (PHM) provide a novel approach for condition-based reliability assessment in engineering systems
      - These could significantly reduce separation distances but has not yet been applied to H2 systems in a risk or safety context.

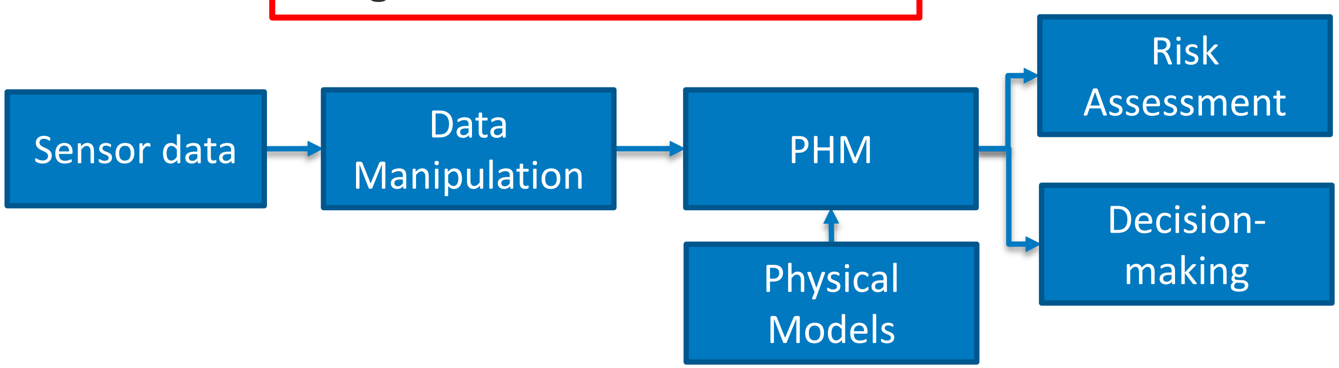
- FirstElement Fuel, Inc.
  - Relation: Collaborator
  - Industry partner
  - Outside of the DOE Hydrogen and Fuel Cells Program
  - Objective: Provide additional failed components for testing and insights into station design and operation

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

UMD Approach: Initial Research Questions

- Core research questions over the next few years seek to define how Prognosis and Health Management (PHM), QRA (Quantitative Risk Assessment), and reliability data can be integrated to support safety, codes and standards
  - How could PHM techniques be used to support development of risk mitigation measures?
  - What kind of data is required for PHM application in liquid hydrogen (LH2) storage?

Can separation distances be reduced with PHM-based risk mitigation measures?



Conceptual PHM architecture

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

Remaining Challenges and Barriers

- Ongoing upgrades to NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF) limit the availability of test time

- Limited availability of failed components with a known failure mode reduces the quantity and variety of components that have been tested

Proposed Future Work

- Complete leak rate testing on components with different failure modes
  - Leaking through (e.g. valves that have been closed but don't seal)
  - Leaking out (e.g. leaks through valve packing to the environment)
- Complete leak rate testing on varied components
  - Needle valves and air actuated valves
  - Ball valves
  - Thermocouples
- Develop a method to securely communicate data and results with the Codes and Standards Community

Generating a larger body of leakage data and distributing it to key stakeholders will improve their ability to make informed, risk-based decisions

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

UMD: Future Work & Potential Impact

UMD will bring the expertise to demonstrate the impact of this data in QRA applications

Future work:

- Identify failure modes and risk scenarios for a LH2 on-site storage station design.
- Select (& identify any gaps in) data sources for reliability of LH2 components
- Identify sources of condition monitoring data needs & define inputs to PHM/QRA algorithm.
- Formulate a PHM framework for applications in LH2 storage

Impact:

- Assessment of PHM techniques contributions as risk mitigation measures e.g., separation distance reduction
- Identification of potential changes to NFPA 2 or ISO 19880-1 regarding use of PHM & QRA for, e.g., safety distances, alternative means and measures, and performance-based RCS.

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

Technology Transfer Activities

- Test data are being catalogued for easy sharing with stakeholders in the risk and hazard evaluation communities
- The project is being introduced to one facet of the codes and standards community via a planned presentation to the NFPA 2 Hydrogen Storage Task Group
  - We will seek input from this group regarding how the data could be best shared with this group
  - We will also seek out other, similar groups to present this project and invite feedback

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

Summary

- An understanding of the actual size of leaks in failed hydrogen components can improve and revise hydrogen Safety Codes and Standards
- A test apparatus for the collection of leak size data from real components was designed and fabricated
- Initial test data have shown the promise of this new capability
- Additional testing will be conducted on components to create a data set of flow conditions
- Data will be made accessible to the community

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

Thank You

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Publication Number

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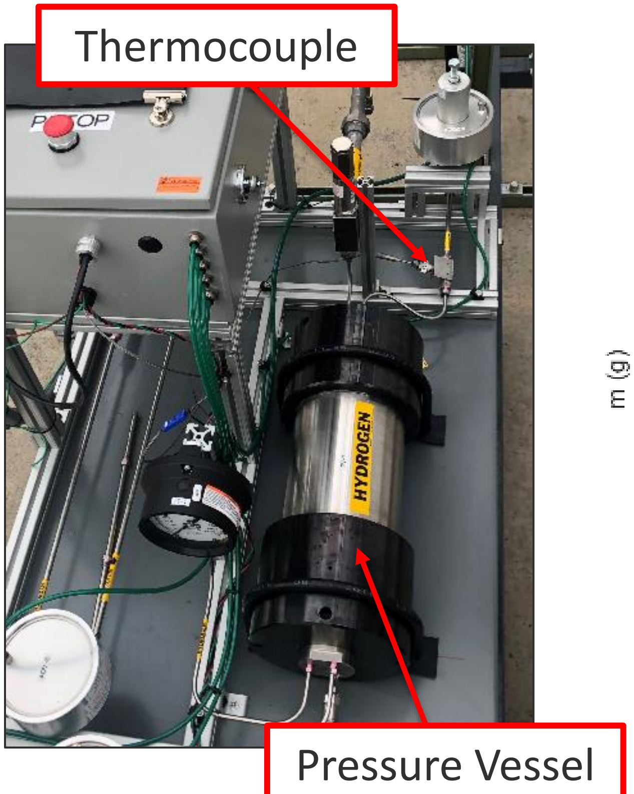
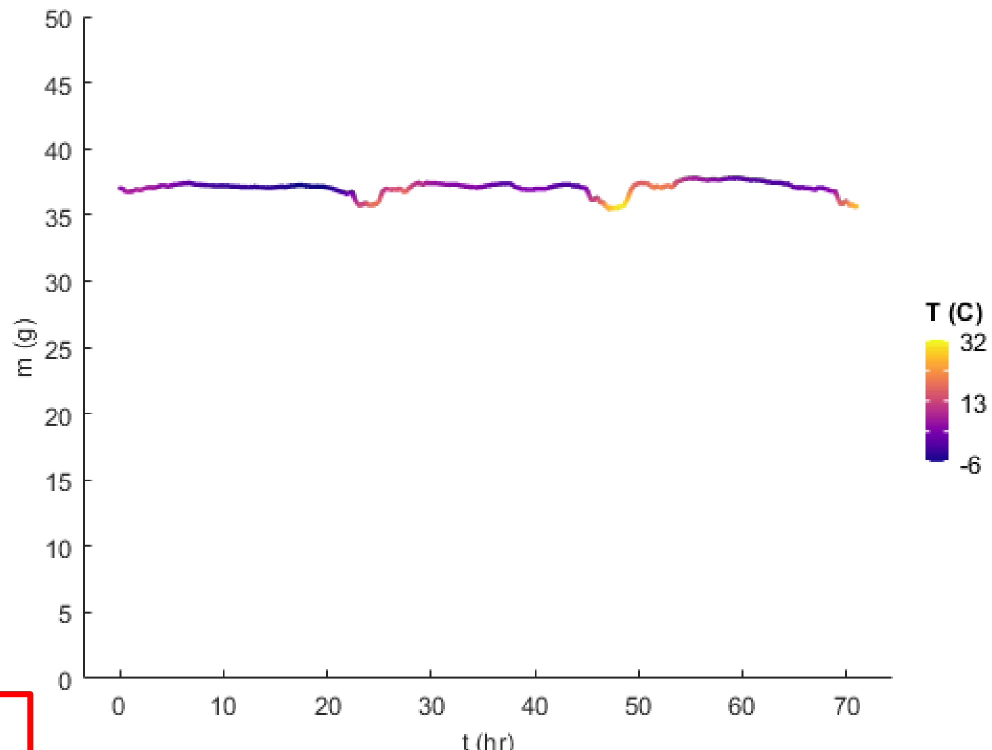
Technical Back-Up Slides

Data from the Pressure Vessel Leak Check

The calculated mass of hydrogen did not show a significant trend that would indicate leakage during a pressure hold of over 70 hours.

- Deviation in the calculated mass is correlated with temperature; likely because thermocouple is located just downstream of the pressure vessel and warms more quickly in the sun, thus underestimating the bulk density





Orifice Calibration Data from CEESI

- The orifice calibration was conducted by CEESI using dry air at a range of Reynolds number values from ~100k-400k. Those data are transcribed in the table below.
- Calibrated orifice data was used in our model by comparing our values to the fourth-order polynomial fit relating Re to C_d (below) provided by CEESI along with the raw calibration data

$$C_d = 8.6629 * 10^{-1} + 2.8545 * 10^{-7} * Re^1 - 1.7059 * 10^{-12} * Re^2 + \cdots$$
$$4.4248 * 10^{-18} * Re^3 - 4.2596 * 10^{-24} * Re^4$$

Pt.	P (psia)	T (°R)	Cd	Re	m_dot (lbm/s)	C*
1	1951.941	536.1	0.88101	373174	0.0039373	0.7183
2	1948.335	536.1	0.88197	373025	0.0039341	0.7183
3	1869.189	535.7	0.88307	361056	0.003775	0.7172
4	1620.858	534.6	0.88266	320187	0.0032592	0.7137
5	1624.883	535	0.88181	320334	0.003263	0.7137
6	1479.947	534.4	0.88217	295581	0.0029654	0.7115
7	1370.469	534.2	0.88222	276124	0.0027398	0.7097
8	1350.307	534.1	0.88315	272874	0.0027017	0.7094
9	1349.833	534.1	0.88308	272755	0.0027005	0.7094
10	1740.284	535.4	0.88201	339597	0.0035022	0.7154
11	1740.846	535.5	0.88151	339470	0.0035012	0.7154
12	1227.162	533	0.88317	250783	0.002451	0.7075
13	1095.954	532.8	0.88364	226243	0.0021836	0.7052
14	1095.978	532.9	0.88363	226196	0.0021833	0.7052
15	962.732	532.6	0.88365	200580	0.0019122	0.7029
16	835.645	532.3	0.88373	175588	0.0016549	0.7006
17	835.103	532.3	0.88396	175531	0.0016543	0.7006
18	708.614	532.1	0.88369	150050	0.001399	0.6983
19	581.488	531.8	0.8826	123873	0.001143	0.6959
20	581.482	531.9	0.88276	123884	0.0011431	0.6959

Pt.	P (psia)	T (°R)	Cd	Re	m_dot (lbm/s)	C*
21	449.212	531.6	0.88157	96232	0.0008789	0.6934
22	449.33	531.7	0.88164	96261	0.0008792	0.6934
23	2145.891	531.1	0.88106	407358	0.0043741	0.7224
24	2146.434	531	0.88129	407595	0.0043767	0.7225
25	2010.6	530.5	0.88239	387430	0.004097	0.7207
26	2075.282	530.7	0.88159	397010	0.004229	0.7215
27	2076	530.7	0.88205	397374	0.004233	0.7216
28	2002.11	530.3	0.88284	386395	0.0040818	0.7206
29	1870.31	529.8	0.88368	365887	0.0038087	0.7188
30	1870.95	529.9	0.88356	365934	0.0038095	0.7188
31	1740.51	529.5	0.88372	344607	0.0035362	0.7168
32	1743.68	529.4	0.88391	345265	0.003544	0.7169
33	1607.71	528.9	0.88427	322467	0.0032611	0.7148
34	1608.41	528.9	0.88425	322580	0.0032624	0.7148
35	1487.69	528.4	0.8844	301656	0.0030113	0.7129
36	1488.06	528.4	0.88427	301667	0.0030116	0.7129
37	1358.45	528	0.88451	278491	0.0027426	0.7107
38	1358.84	528	0.88447	278545	0.0027433	0.7107
39	1237.39	527.9	0.88356	255727	0.0024882	0.7086
40	1238.34	527.9	0.88351	255892	0.00249	0.7086

Table of Test Points for Calibrated Orifice

Test	Fluid	P start (Pa)	T (K)	Estimated d_{nt} (in)
1	Nitrogen	3.02E+06	300.3	0.0104 (± 0.0002)
2	Nitrogen	2.97E+06	297.9	0.0104 (± 0.0002)
3	Nitrogen	2.96E+06	296.3	0.0104 (± 0.0002)
4	Nitrogen	6.68E+06	293.8	0.0103 (± 0.0001)
5	Nitrogen	6.37E+06	292.7	0.0103 (± 0.0001)
6	Nitrogen	6.32E+06	291.6	0.0103 (± 0.0001)
7	Nitrogen	8.18E+06	289.4	0.0103 (± 0.0001)
8	Nitrogen	7.80E+06	288.1	0.0104 (± 0.0001)
9	Nitrogen	1.22E+07	275.9	0.0102 (± 0.0001)
10	Nitrogen	1.21E+07	276.1	0.0103 (± 0.0001)
11	Nitrogen	1.19E+07	276.6	0.0103 (± 0.0001)
12	Nitrogen	9.35E+06	279.0	0.0103 (± 0.0001)
13	Nitrogen	9.62E+06	279.4	0.0103 (± 0.0001)
14	Nitrogen	9.54E+06	280.4	0.0103 (± 0.0001)
15	Hydrogen	2.77E+06	270.0	0.0101 (± 0.0002)
16	Hydrogen	2.65E+06	269.5	0.0108 (± 0.0002)
17	Hydrogen	2.52E+06	269.6	0.0109 (± 0.0001)
18	Hydrogen	5.43E+06	269.7	0.0107 (± 0.0002)
19	Hydrogen	5.53E+06	269.1	0.0107 (± 0.0001)
20	Hydrogen	5.64E+06	269.1	0.0108 (± 0.0002)
21	Hydrogen	8.23E+06	268.4	0.0107 (± 0.0001)
22	Hydrogen	8.28E+06	268.0	0.0104 (± 0.0001)
23	Hydrogen	8.06E+06	267.9	0.0107 (± 0.0002)
24	Hydrogen	9.32E+06	267.6	0.0106 (± 0.0001)

The calibrated orifice was tested 24 times using the LRQA at varied starting pressure and with both nitrogen and hydrogen.

The stated uncertainties are based only on the variance within test points and do not reflect the total uncertainty of the system.

Test Procedure

1. Identify a component with known leaks that does not show mechanical damage
2. Purge pressure vessel with the test gas
3. Pressurize the pressure vessel to the test pressure
4. Isolate the pressure vessel allowing the pressure and temperature to stabilize
5. Connect the pressure vessel to the device under test
6. Monitor and log the change in pressure and temperature at the vessel and the device under test
7. Stop the test when the pressure has dropped to 100 psi or when 20 minutes have elapsed
8. Repeat test steps 3-7 increasing the test pressure until the maximum supply pressure is reached