Tatsuno Coriolis Flow Meter Development Testing in High Pressure Hydrogen

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June 14, 2018

DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID # H2004

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

Overview

Timeline and Budget

- Project start date: 10/01/18
- Project end date: 10/01/19
- Total project budget: $60K
  - CRADA Call DOE $30K
  - Tatsuno Cost Share $30K
  - Total DOE funds spent*: $30K

* As of 3/31/18

Barriers

- Measurement accuracy for hydrogen as a motor vehicle fuel
- Lack of high pressure hydrogen testing facilities
- Limited number of high pressure hydrogen compatible devices

Partners

- Tatsuno

Relevance: Project Objectives

To provide high pressure hydrogen test validation on new coriolis flow meter product

New product design features:

- Compact design
- Improved accuracy
- Remote operation with Modbus and Bluetooth communication

Proprietary data taken on the new Tatsuno flow meter is being shared with the manufacturer; data shown is representative composite data taken during meter benchmark testing

Relevance: Problem Statement

70 MPa hydrogen motor vehicle dispensing has not been able to meet accepted ±2.0% accuracy standards

Metrology Projects and Progress

- California DMS Metrology Standard
- Reduced Accuracy Classes (CCR & NIST)
- DOE/NREL Meter Benchmarking
- Other NREL metrology collaborations
  - Tatsuno CRADA
  - IVYS Project
  - Air Liquide/CSA
  - Emerson (Micro Motion)

Relevance: Problem Statement

California Code of Regulations adopted relaxed regulations to NIST Handbook 44 accuracy classes for hydrogen meter accuracy. Those relaxed regulations will begin to sunset in 6 months.

Table T.2.
Accuracy Classes and Tolerances for Hydrogen Gas-Measuring Devices

Accuracy Class	Application or Commodity Being Measured	Acceptance Tolerance	Maintenance Tolerance
2.0		1.5 %	2.0 %
~~3.0~~ [1]	Hydro	~~%~~	~~3.0 %~~
~~5.0~~ [1]		~~4.0 %~~	~~5.0 %~~
~~10.0~~ [2]		~~%~~	~~10.0 %~~

January 1, 2020

January 1, 2018

All of the dispensers in California have been certified to accuracy class 5.0*

* *As of 3/1/2017 Source:* https://www.cdfa.ca.gov/dms/ctep.html

NIST Handbook 44 Amended Accuracy Class

NIST Handbook 44 has amended the ±1.5 Acceptance and ±2.0 Maintenance tolerances to ±5.0 and ±7.0 respectively, based on data from California station certification

NIST Handbook 44 - 2017

3.39. Hydrogen Gas-Measuring Devices – Tentative Code

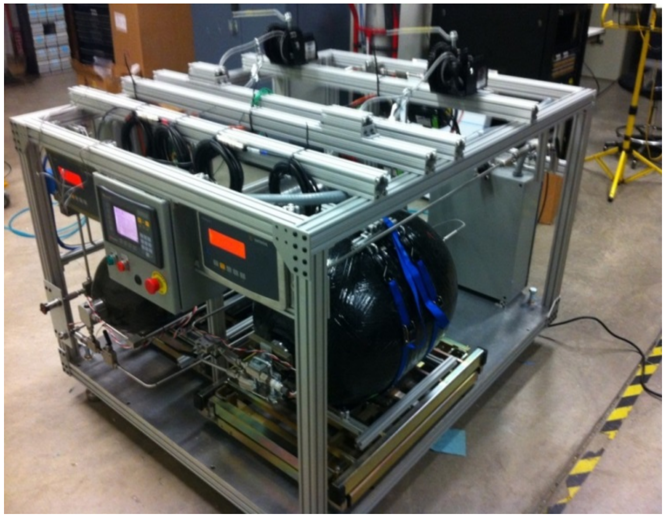
T.2. Tolerances. – The tolerances for hydrogen gas measuring devices are listed in Table T.2. Accuracy Classes and Tolerances for Hydrogen Gas-Measuring Devices. (Proposed tolerance values are based on previous work with compressed gas products and will be confirmed based on performance data evaluated by the U.S. National Work Group.)

Table T.2.
Accuracy Classes and Tolerances for Hydrogen Gas-Measuring Devices

Accuracy Class	Application or Commodity Being Measured	Acceptance Tolerance	Maintenance Tolerance
7.0	Hydrogen gas as a vehicle fuel	5.0 %	7.0 %

(Amended 2016)

California Station Metrology Device



California DMS contracted with NREL to build the metrology standard that is being used for hydrogen station certification

Benchmark Testing

- **Designed, built, and tested gravimetric hydrogen standard**
  - System error: worst case = ±2.5 grams (calculation in technical backup slides)
- **Completed flow testing on three hydrogen flow meters**
  - M1: Coriolis—commercially available—designed for H_2 applications
  - M2: Coriolis—in development—designed for H_2 applications
  - M3: Turbine—commercially available—adjusted for H_2 application

Test Plan

Testing was designed to span the ranges of typical fueling conditions for light duty fuel cell electric vehicles

- The meters were subjected to short fills in the range of 0.5 to 1.2 kg dispensed
- Considered to be one portion of a typical SAE J2601 fill

<table>
<tr><td colspan="6">Pressure Ramp, psi/min (MPa/min)</td></tr>
<tr><td colspan="2">Low - LR</td><td colspan="2">Medium - MR</td><td colspan="2">High - HR</td></tr>
<tr><td colspan="2">3,000 (20.7)</td><td colspan="2">6,000 (41.4)</td><td colspan="2">10,000 (68.9)</td></tr>
<tr><td colspan="6">Mass Flow Rate, kg/min</td></tr>
<tr><td colspan="2">Low - LF</td><td colspan="2">Medium - MF</td><td colspan="2">High - HF</td></tr>
<tr><td colspan="2"><1</td><td colspan="2">1 - 2</td><td colspan="2">>= 2</td></tr>
<tr><td colspan="6">Meter Position</td></tr>
<tr><td colspan="3">Position 1 - P1</td><td colspan="3">Position 2 - P2</td></tr>
<tr><td colspan="3">Upstream of Control Valve
Held at Constant Pressure</td><td colspan="3">Downstream of Contorl Valve
Experiences Pressure Ramp of Fill</td></tr>
<tr><td colspan="6">Inlet Pressure, psi (MPa)</td></tr>
<tr><td colspan="3">Low - L</td><td colspan="3">High - H</td></tr>
<tr><td colspan="3"><= 6,000 (41.4)</td><td colspan="3">> 6,000 (41.4)</td></tr>
</table>

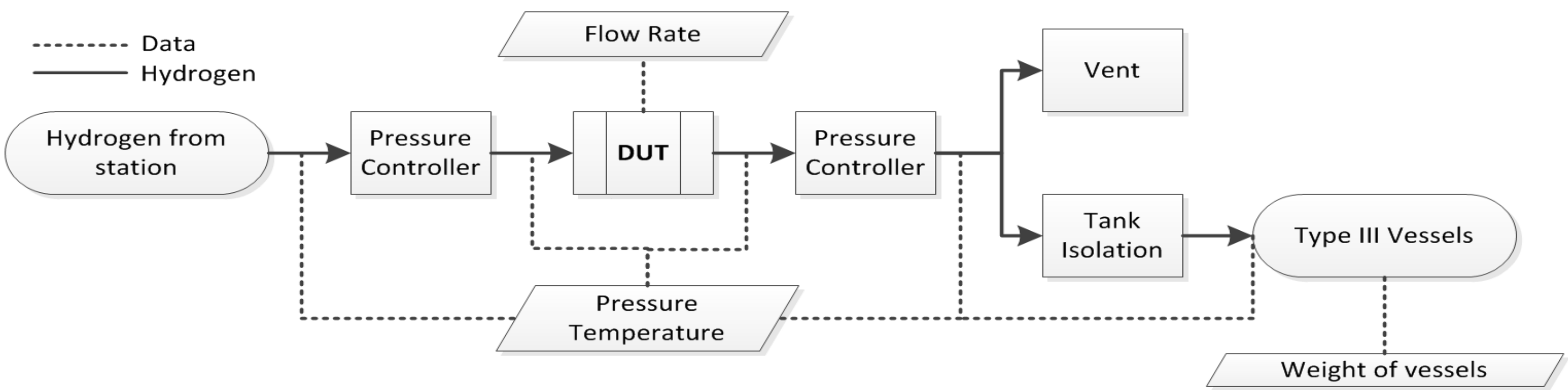
Parameters and Analysis

Parameters

- Meter accuracy
  - Start of fill
  - During steady flow
  - At stop of flow
  - When meter stops incrementing
- Differential pressure
- Differential temperature
- Meter readout delay

Analysis

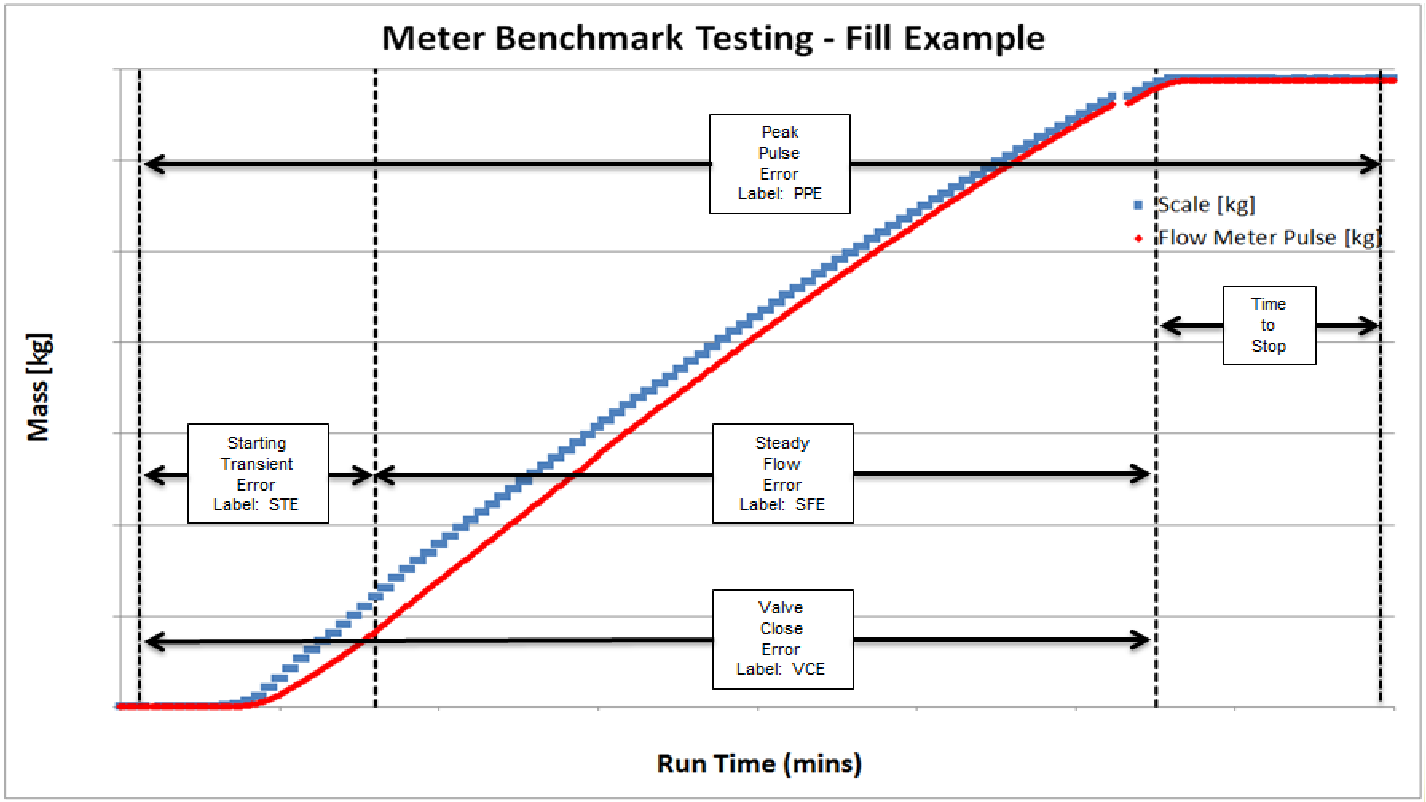
- Analysis of Variance (ANOVA)
  - Explore the different factors (e.g., position, flow rate, high vs. low pressure)
- Distribution plots
  - Determine the probability that one fill would fall within certain accuracy classes



Typical Fill Profile

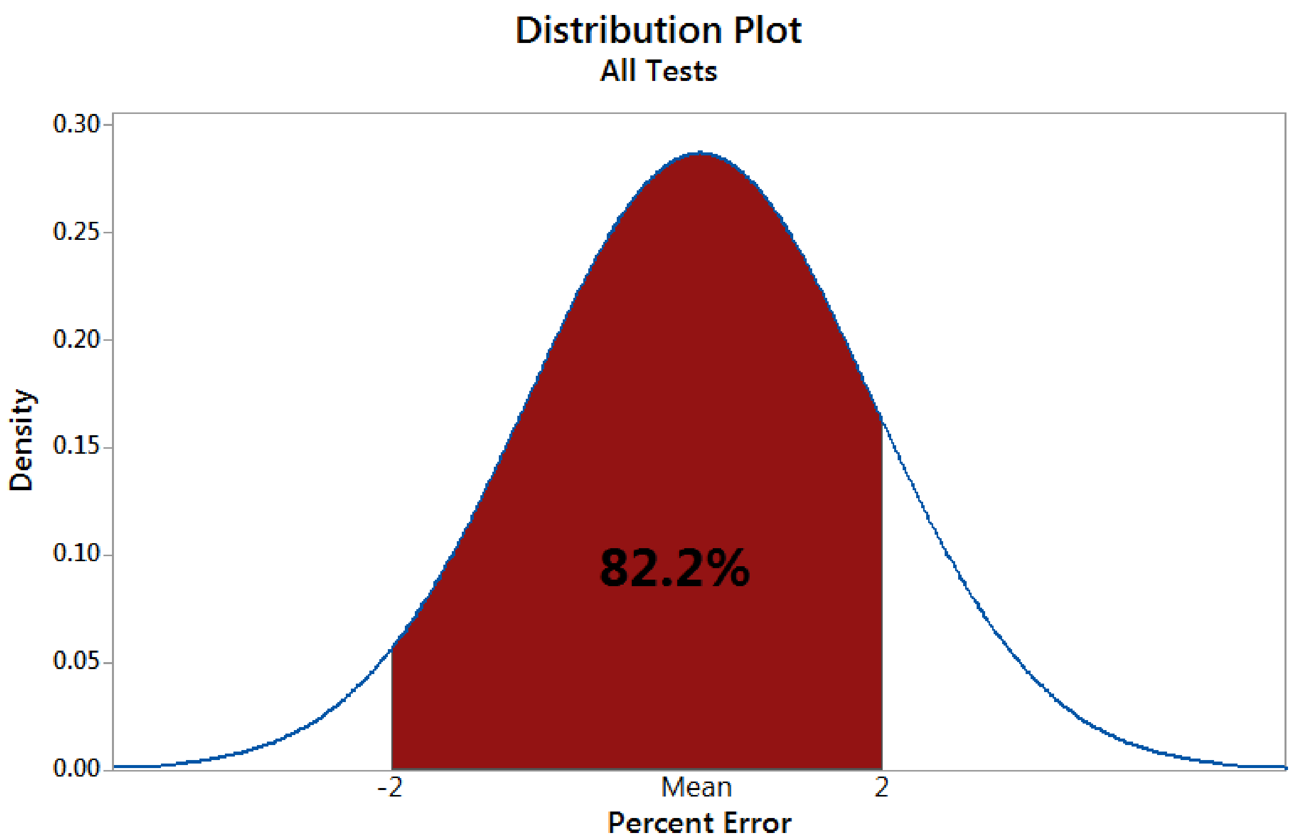
$$Meter\ Error\ (at\ any\ time) = \frac{\Delta Meter\ - \Delta Scale}{\Delta Scale}$$

+ Error means meter is reading high and customer is being charged more
- Error means meter is reading low and customer is being charged less



Distribution Plot – All

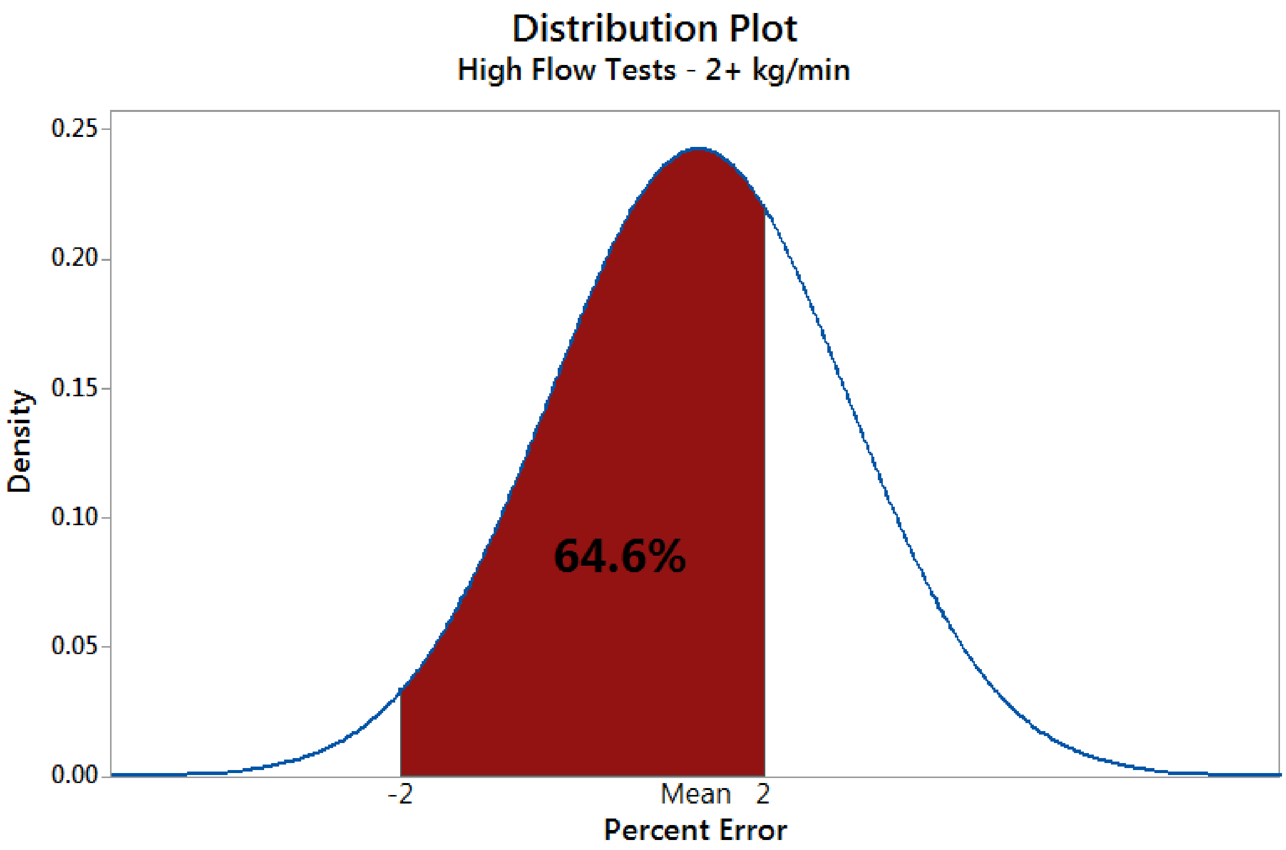
Best meter: With all of the fill data collected, the probability a single fill will be within ±2% is 82.2%



Factors and Levels in Data Set
Pressure Ramp LR, MR, and HR
Mass Flow Rate LF, MF, and HF
Meter Position P1 and P2
Inlet Pressure L and H

Distribution Plot – High Flow

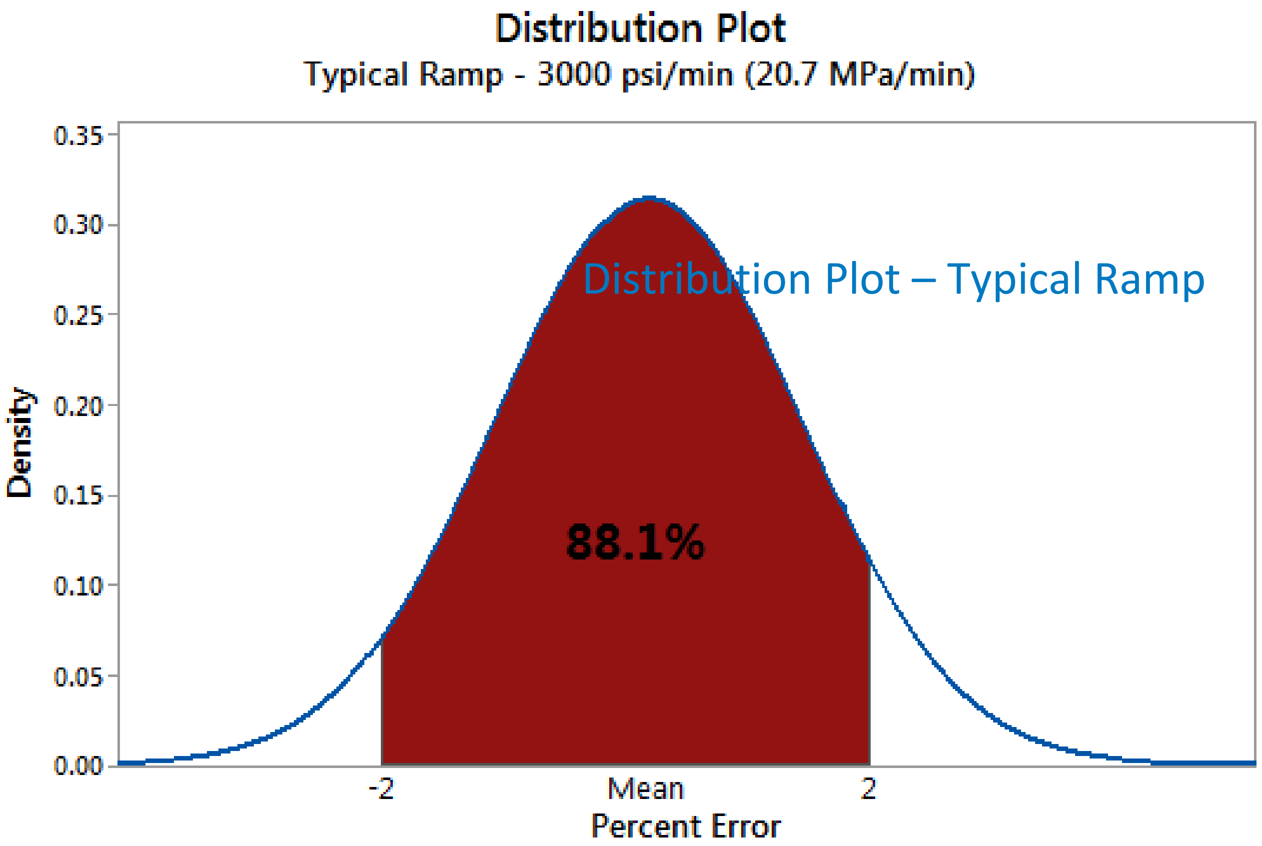
Best meter: With the high flow (2+ kg/min) fill data collected, the probability a single fill will be within ±2% is 64.6%



Factors and Levels in Data Set
Pressure Ramp MR or HR
Mass Flow Rate Only HF (2+ kg/min)
Meter Position P1 and P2
Inlet Pressure L and H

Distribution Plot – Typical Ramp

Best meter: With the typical ramp fill data collected, the probability a single fill will be within ±2% is 88.1%

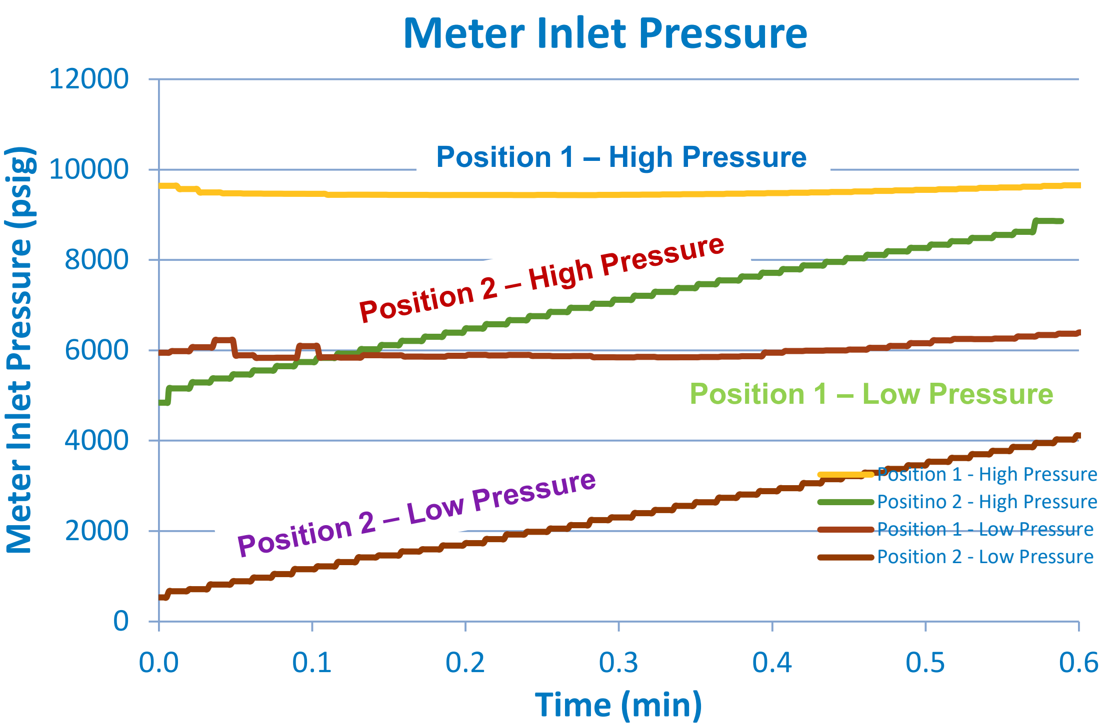


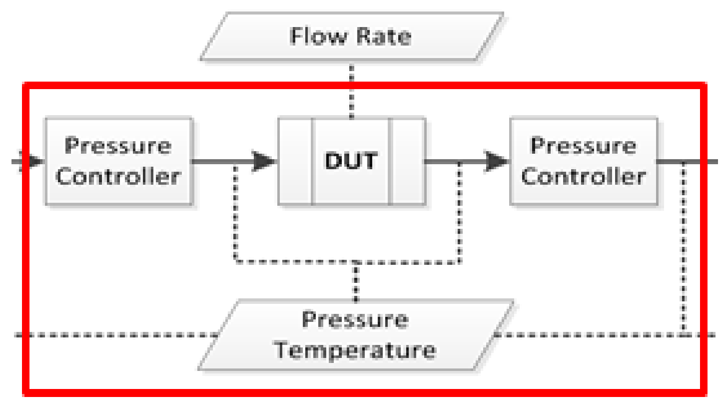
Distribution Plot – Typical Ramp

Factors and Levels in Data Set
Pressure Ramp LR - 3,000 psi/min (20.7 MPa/min)
Mass Flow Rate Varies
Meter Position P1 and P2
Inlet Pressure L and H

ANOVA – Position

Coriolis Meters: **No** significant difference in meter performance due to meter position.
Turbine meter: Volumetric restriction only allowed testing in Position 1.

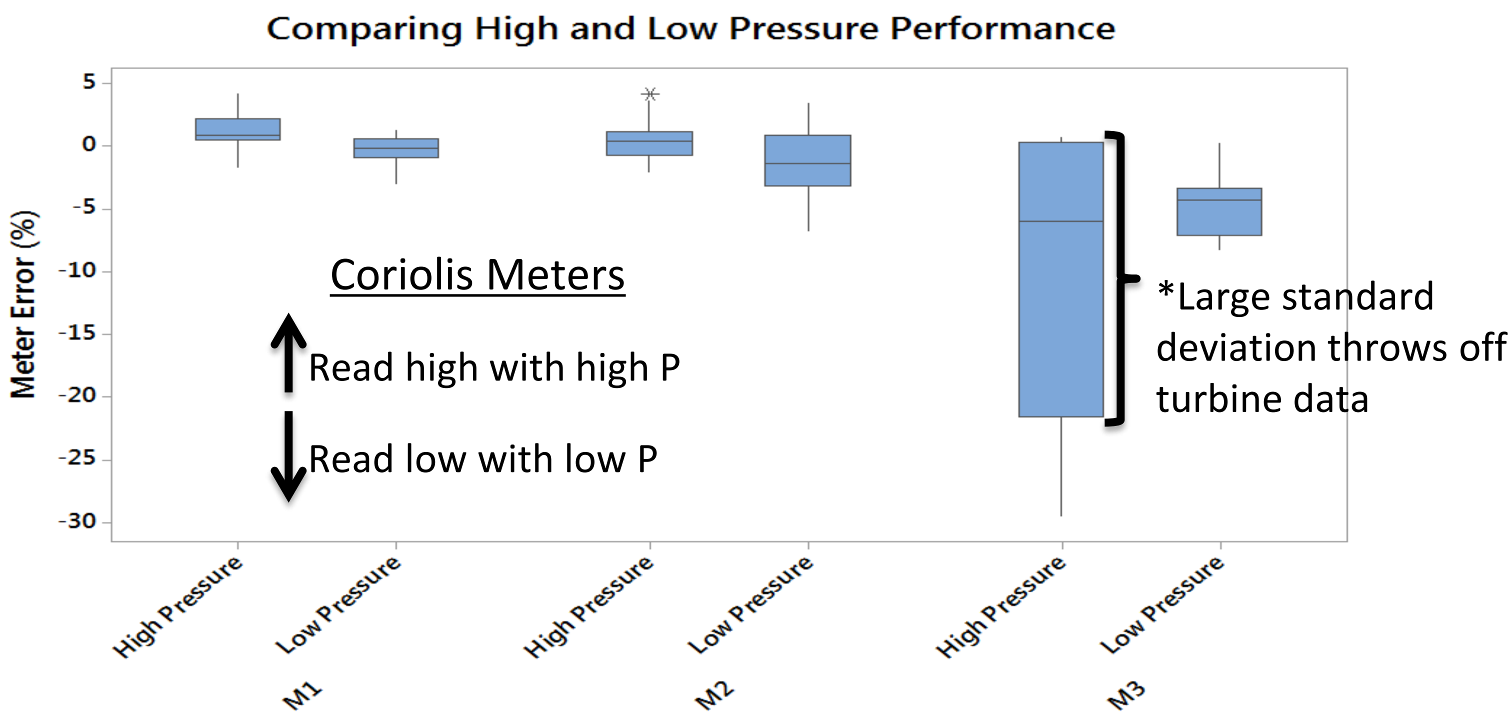




ANOVA – Inlet Pressure

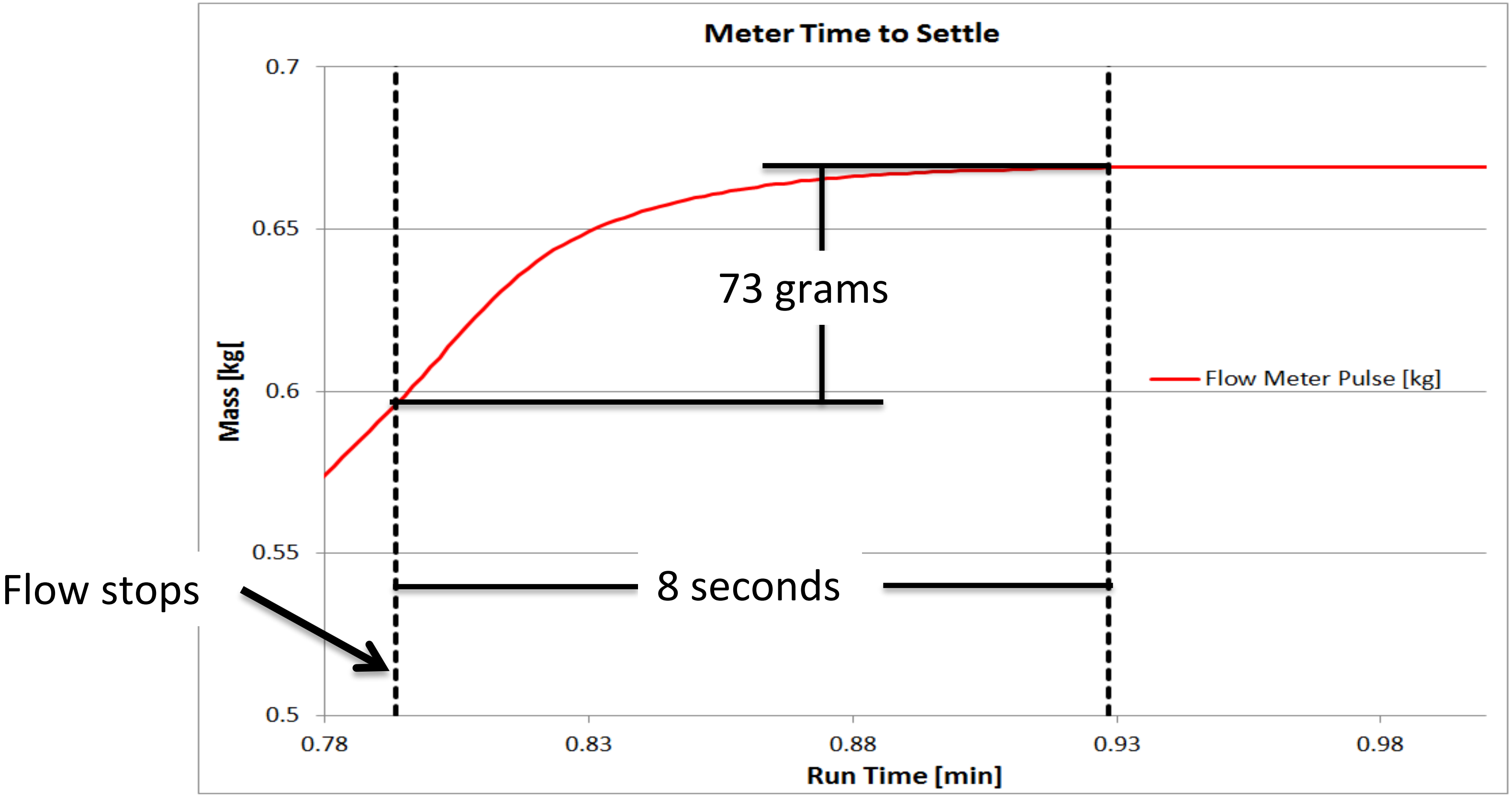
Coriolis meters: Significant difference in meter performance due to meter inlet pressure.

Turbine meter: **No** significant difference in meter performance due to meter inlet pressure*.



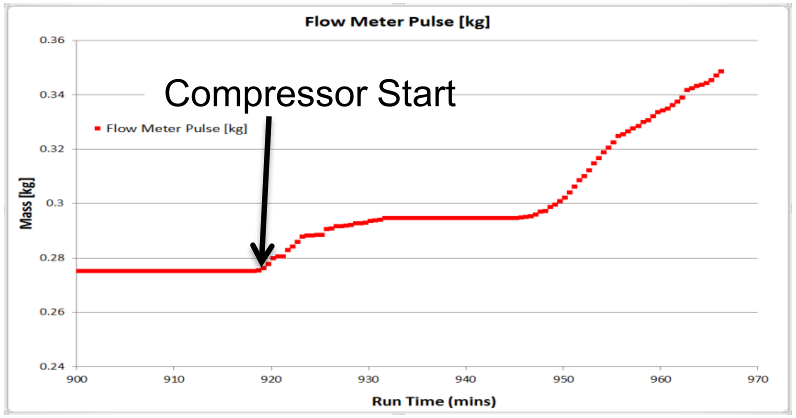
Meter Delay

Two of the devices under test had delays less than 2 sec, however, one meter had a delay in the 7–9 sec range

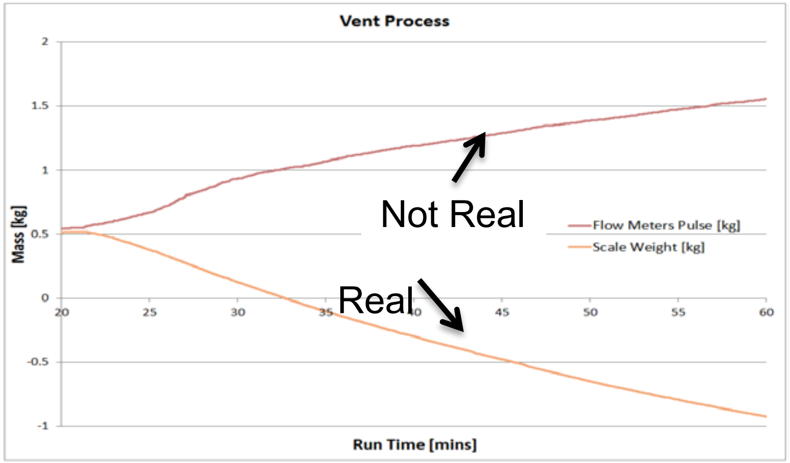


Vibration

False readings of a Coriolis meter 30 feet away from a compressor



False readings of a Coriolis meter from nearby venting



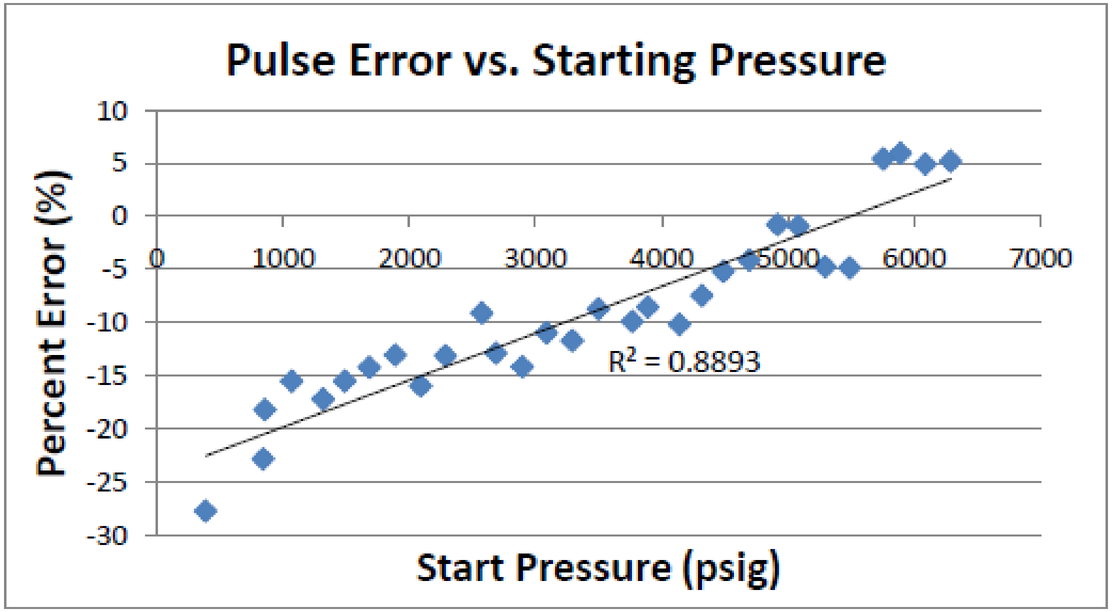
Pulse Testing

Methodology

- Testing spanned from 40–120 grams and percent error was calculated
- Inlet pressure ranged from 100–6,000 psig (0.7–41 MPa) to simulate a typical car coming in empty to partially empty

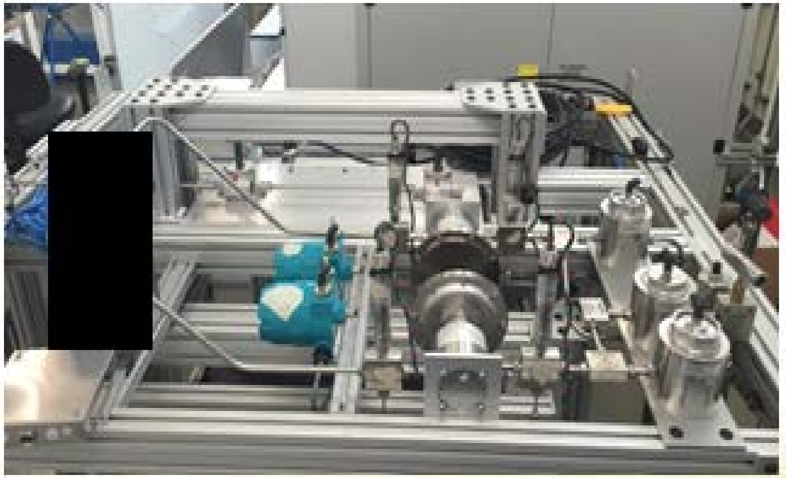
Conclusion

- Meter accuracy was low during pulse testing, however, we did see patterns that station operators could integrate into dispenser controls



Lessons Learned

- Differential pressure
  - The Coriolis meters had a much high differential pressure than the turbine meter
  - Under high flow conditions the Coriolis meters had a maximum differential pressure of 600–700 psi (4–5 MPa)
- Differential temperature
  - All flow meters showed a 1 to 3 ^{o}C change in temperature during flow testing
  - The testing was not completed with pre-chilled hydrogen which could cause larger differential temperatures across the meter
- Vibration (Coriolis Meters Only)
  - Observed false readouts on meters due to vibration from hydrogen compressors, venting tubing, or simply tapping on the support system
- Meter Delay
  - Time between when flow stopped and when the meter stopped incrementing was very different for each meter



Meter Collaboration

Tatsuno Meter Testing Delegation (Left to Right in photo, Mike Peters, Matt Post, Ichi Emori, Sean Chigusa, Norikazu Osawa, Tsutomu Otaki), photo by Rob Burgess

Design Reviews

- Gravimetric standard test apparatus design review was held at NIST Gaithersburg
- Project partners were used to review project test plan (SNL, NIST, CDFA, CARB, JRC-IET and BMW)

Meter Manufacturers

- Meter manufacturers were consulted during meter selection process; Further testing is being conducted with Tatsuno and IVYS

State Metrologist

- California Division of Measurement Standards was consulted to utilize field data from dispenser certification
- Working with northeast station developers (Air Liquide/CSA) to share information for development of gravimetric standard to be used for station certification

Stakeholders

- Presented at forums such as Tech Team meetings, Fuel Cell Partnership working group and SAE technical committee meetings

Responses to Reviewer Comments

There is some concern that critical elements specified in J2601 were not tested.

Our test setup was not capable of performing fills with pre-cooled hydrogen which limited the length of fills we could perform. It would have been expensive and time consuming to add pre-cooled capability to our system so the team decided against that option early in the project. That being said the fills here are representative of a section of a SAE J2601 fill.

The ability to share the project's data and insights as closely as possible with equipment manufacturers will likely be the key to this project's ultimate impact

Agreed on sharing the data with the public. We are working towards a publication to get this data out there but it still won't have specific manufacturers called out. CRADA Call H2@Scale has provided NREL for additional funding to further increase the number of data sets. Releasing the data publicly will require approval from project partners.

If the project continues to test commercial meters, as well as pre-commercial/prototypes, perhaps these there should be two separate "arms" of the project.

Agreed on this suggestion. We would have to explore how the tests may be different between a commercial versus developmental but this would be a good approach to future testing.

Summary of Metrology Projects

Best Meter: probability a single fill will be within 2%

- All cases – 82.2%
- High flow – 64.6%
- Typical today – 88.1%

ANOVA Results – Meter Accuracy

- Meter downstream or upstream of the control valve does not matter
- High pressure versus low pressure affects meter performance
- Flow rate does not matter; however, when separated out by position, it does

Practical Use at Stations

- Coriolis: Differential pressure can be up to 700 psig
- Vibration and delay could cause accuracy issues
- Pulse has quantifiable trends

Collaborations

- SNL, NIST, JRC-IET, CDFA, CARB, BMW, Air Liquide, CSA, IVYS, Tatsuno

Proposed Future Research

- Test more commercial or prototype meters
- Develop a controls scheme to improve meter performance in the field

ESIF – Energy Systems Integration Facility

NREL laboratory facility provides laboratory space R&D testing of high pressure hydrogen component and system.

Thank You

www.nrel.gov

Publication Number

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