H2FIRST

Hydrogen Fueling Infrastructure Research and Station Technology

Hydrogen Meter Benchmark Testing
2017 DOE Annual Merit Review

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National Renewable Energy Laboratory

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Project ID # TV037

Overview

H2FIRST

TIMELINE

- Start date: 9/1/2015
- End date: 12/31/2017

BARRIERS

Multiyear RD&D Barriers

Technology Validation Barriers

- ***D.*** Lack of Hydrogen Refueling Infrastructure Performance and Availability Data
- ***E. Codes and Standards -*** *Validation projects will be closely coordinated with Safety, Codes and Standards*

Safety Codes and Standards Barriers

- ***F.*** Enabling national and international markets requires consistent RCS
- ***G.*** Insufficient technical data to revise standards
- ***J.*** Limited participation of business in the code development process

BUDGET

- Project funding FY15/16/17: **$500K**

PARTNERS

- SNL (Sandia National Laboratory)
- NIST (National Institute of Standards and Technology) Fluid Metrology Group
- JRC-IET (Joint Research Center – Institute for Energy and Transport)
- CDFA (California Department of Food and Agriculture) Division of Measurement Standards
- CARB (California Air Resources Board)
- BMW

Relevance: Relaxed Regulations

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.

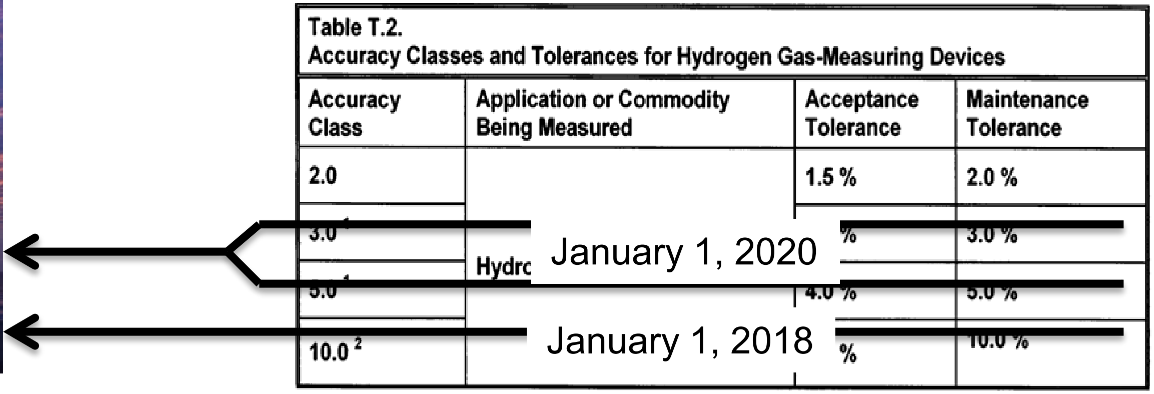


Table T.2.
Accuracy Classes and Tolerances for Hydrogen Gas-Measuring Devices

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

Approach: 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

Approach: 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

Pressure Ramp, psi/min (MPa/min)		
Low - LR	Medium - MR	High - HR
3,000 (20.7)	6,000 (41.4)	10,000 (68.9)

Mass Flow Rate, kg/min		
Low - LF	Medium - MF	High - HF
<1	1 - 2	>= 2

Meter Position	
Position 1 - P1	Position 2 - P2
Upstream of Control Valve Held at Constant Pressure	Downstream of Contorl Valve Experiences Pressure Ramp of Fill

Inlet Pressure, psi (MPa)	
Low - L	High - H
<= 6,000 (41.4)	> 6,000 (41.4)

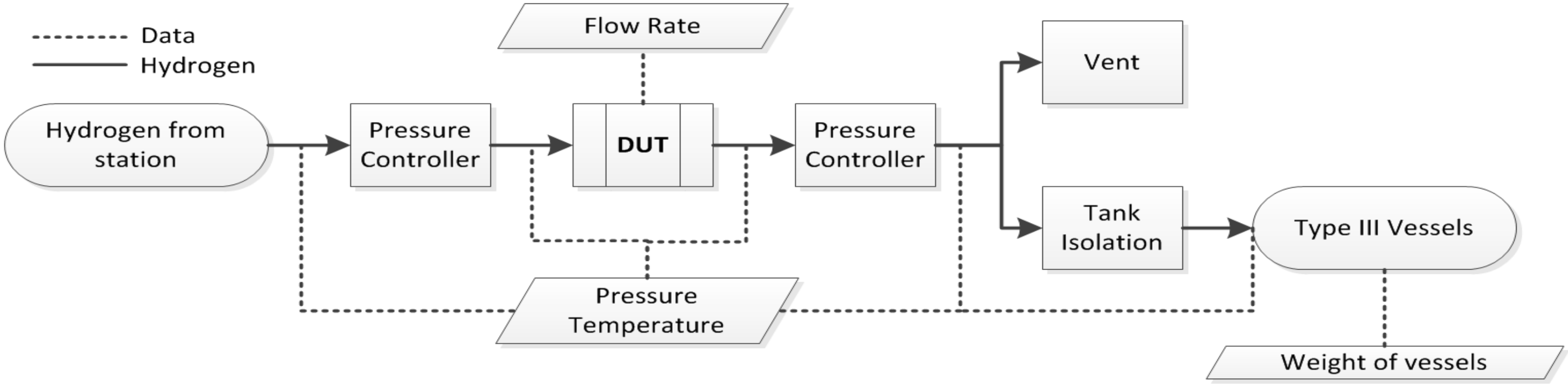
Approach: Parameters and Analysis

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

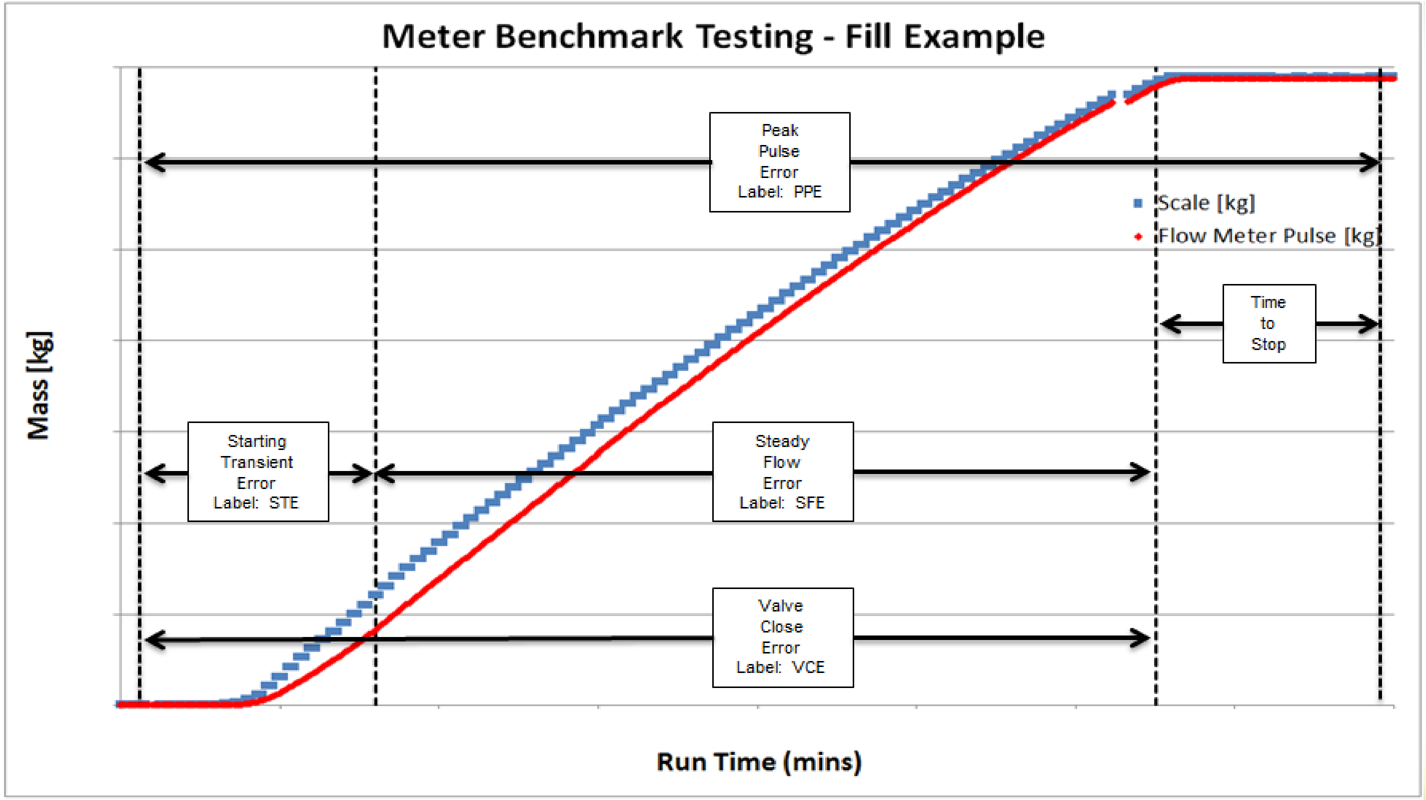


Accomplishment: Typical Fill Profile

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

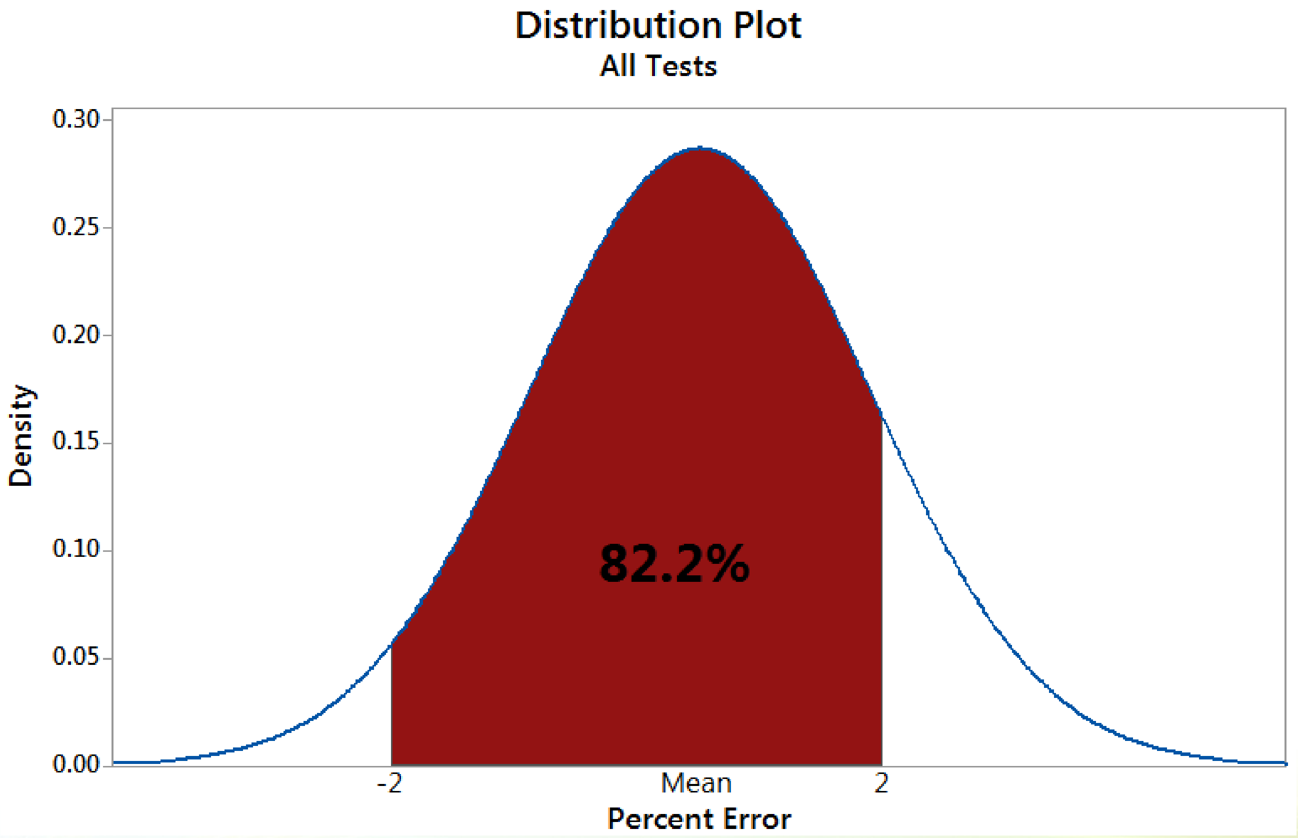
\+ Error means meter is reading high and customer is being charged more

\- Error means meter is reading low and customer is being charged less



Accomp: Distribution Plot - All

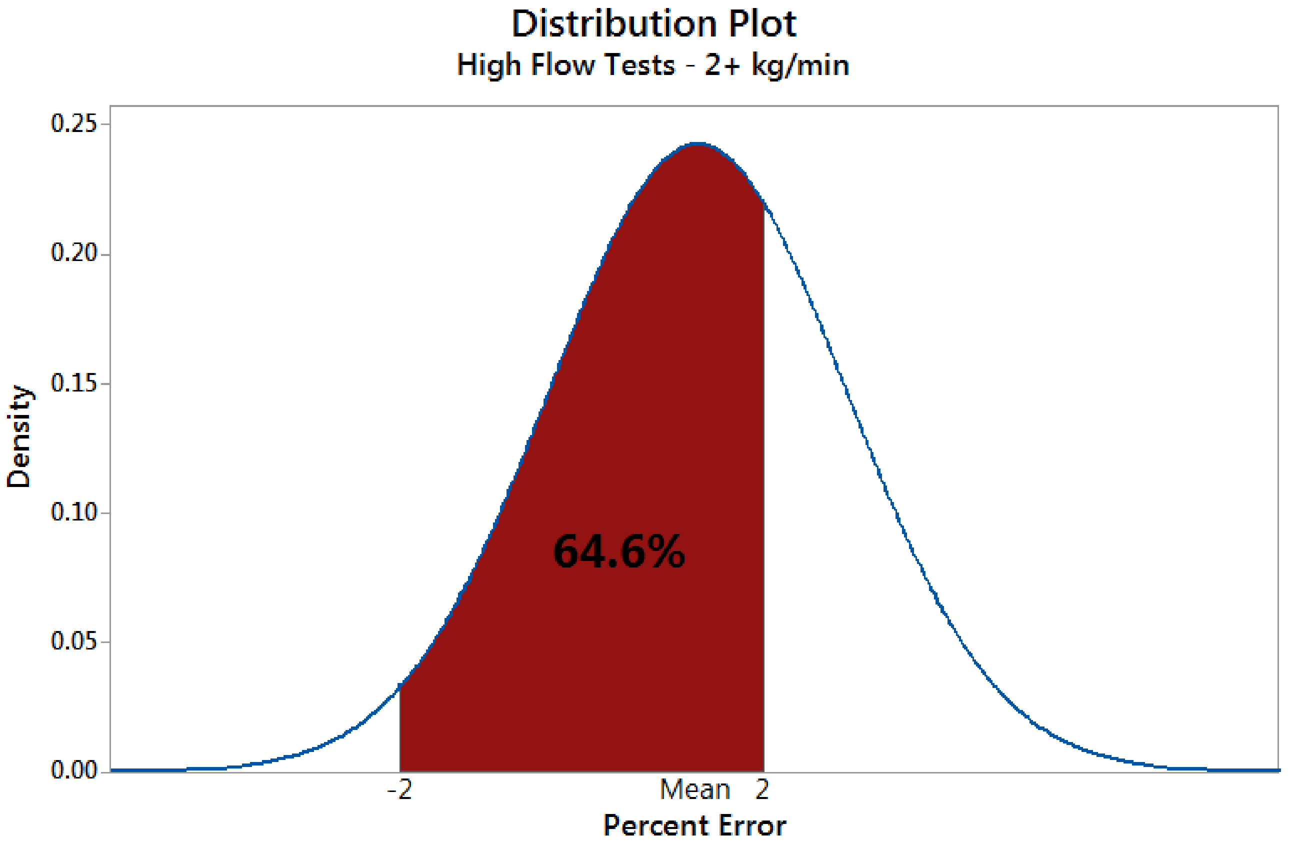
Best meter: With all of the fill data collected, the probability a single fill will be within ± 2% is 82.2%



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

Accomp: Distribution Plot – High Flow

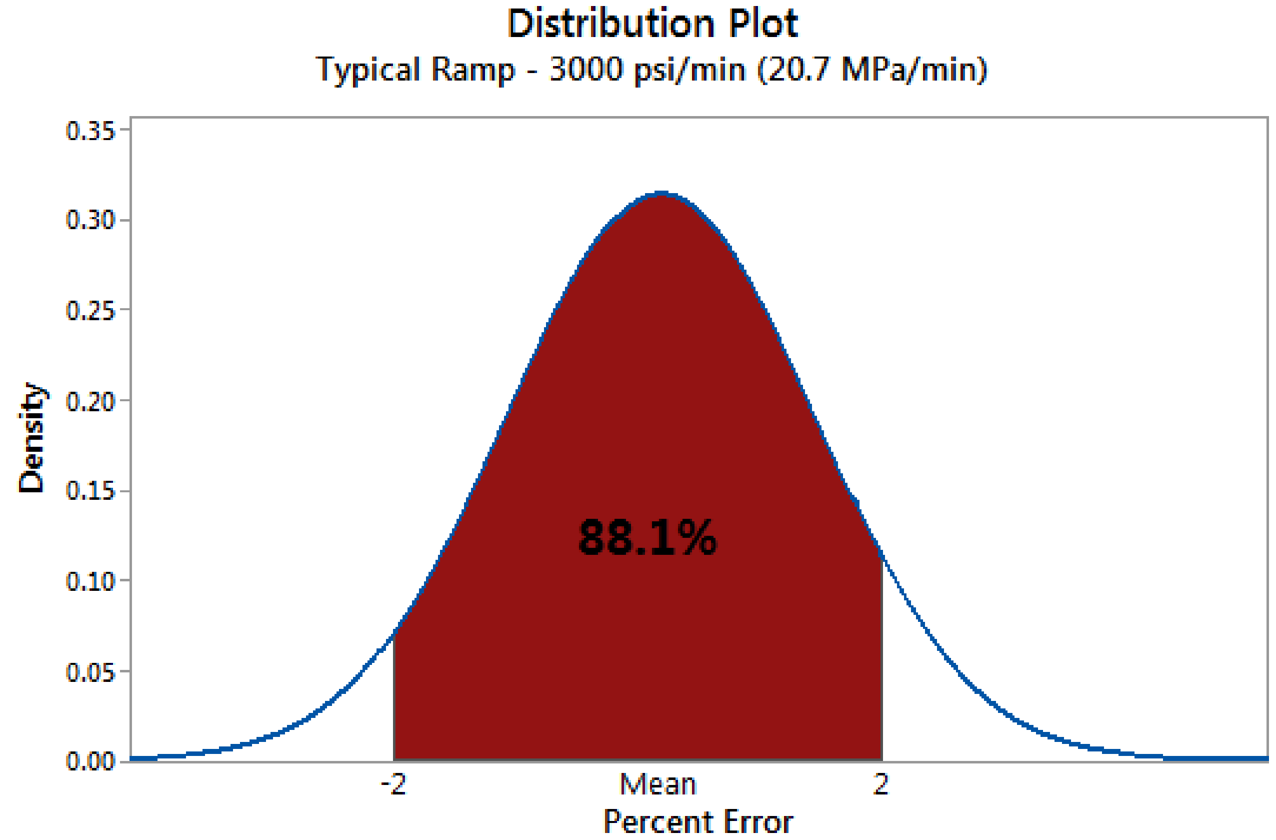
Best meter: With the high flow (2+ kg/min) fill data collected, the probability a single fill will be within ± 2% is 64.6%



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

Accomp: Distribution Plot – Typical Ramp

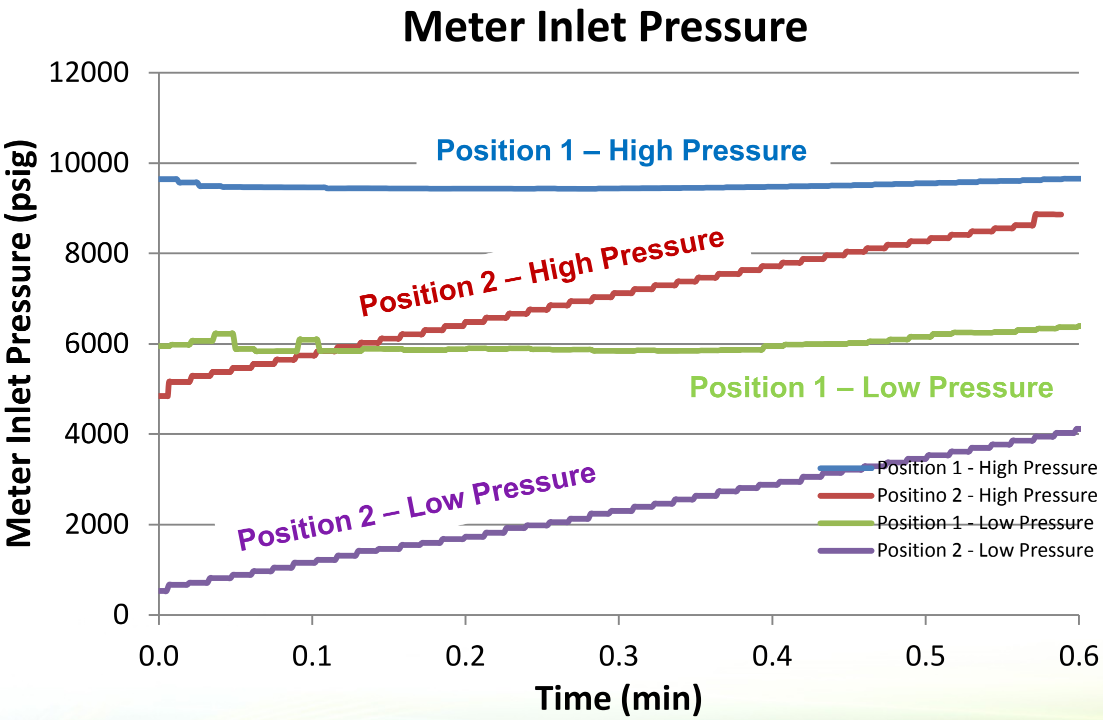
Best meter: With the typical ramp fill data collected, the probability a single fill will be within ± 2% is 88.1%

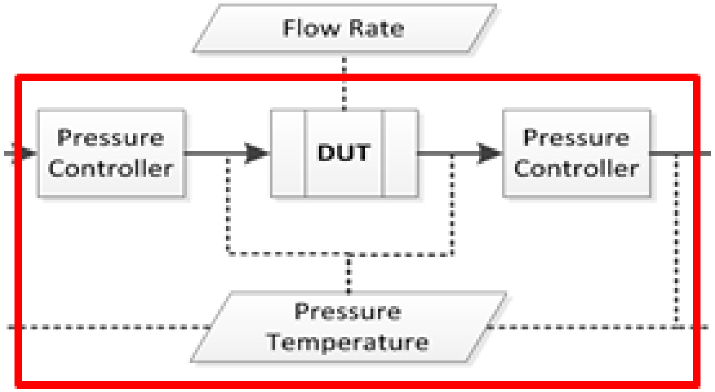


Factors and Levels in Data Set
Pressure Ramp LR - 3,000 psi/min (20.7 MPa/min)
Mass Flow Rate Varies
Meter Position P1 and P2
Inlet Pressure L and H

Accomplishment: ANOVA - Position

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

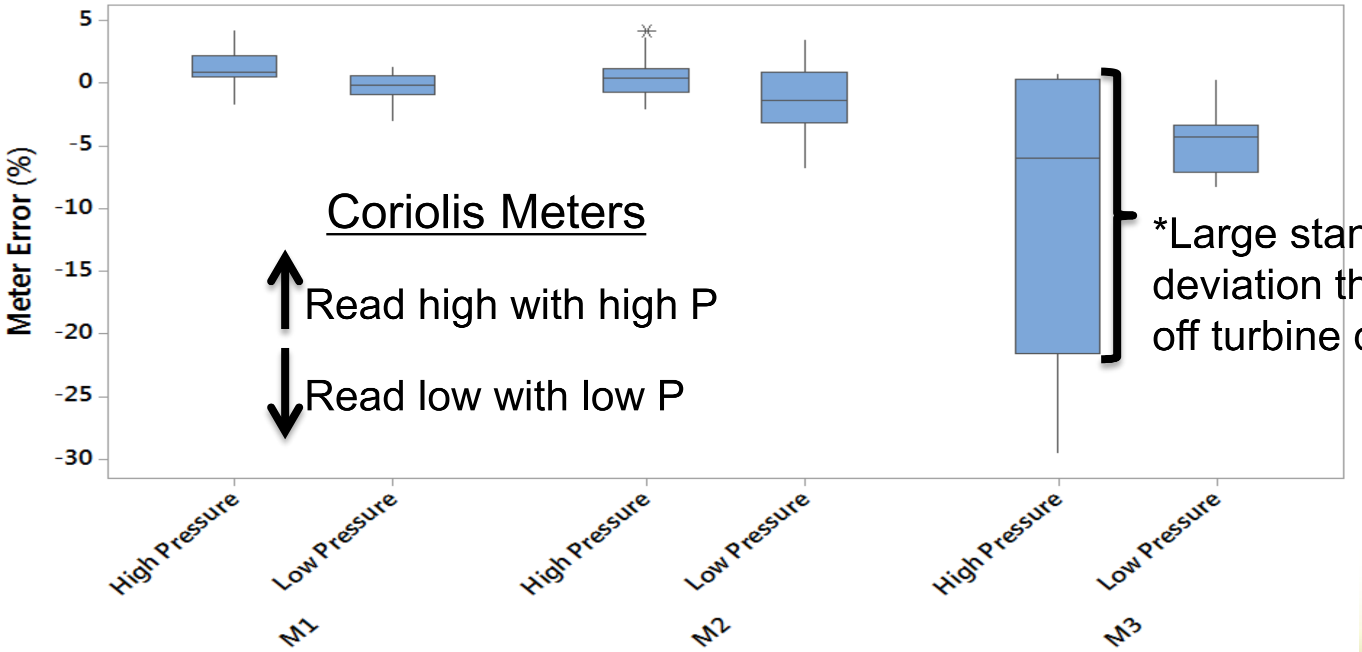




Accomplishment: ANOVA – Inlet Pressure

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*.*

Comparing High and Low Pressure Performance



Coriolis Meters

↑ Read high with high P

↓ Read low with low P

*Large standard deviation throws off turbine data

Accomplishment: ANOVA – Flow Rate

Flow Rate Independence

- Low Flow (<1 kg/min)
- Medium Flow (1 – 2 kg/min)
- High Flow (2+ kg/min)
- Flow meters did not show a significant difference in performance based on flow rate, however, when inlet pressure is taken into account the high flow rate case shows a difference

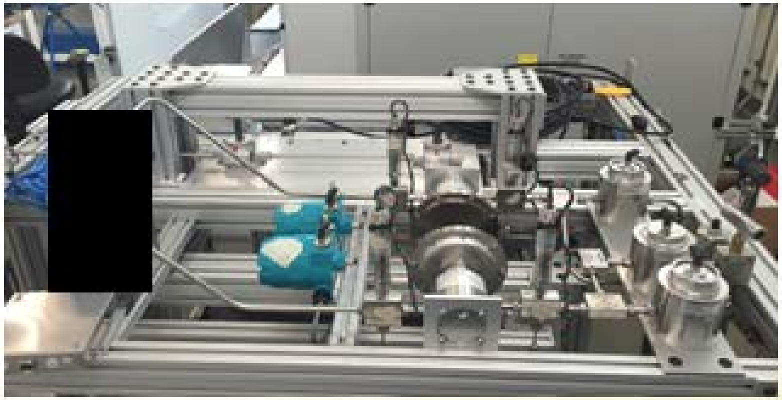
Pressure Dependence at High Flow Rate

- High Flow & Low Pressure vs. High Flow & High Pressure
- Coriolis Meters: High flow and high pressure leads to + error, or the meter reads higher than it should
- Turbine Meter: High flow and high pressure leads to – error, or the meter reads lower than it should

Accomplishment: Practical Implementation

Other parameters measured during testing

- 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



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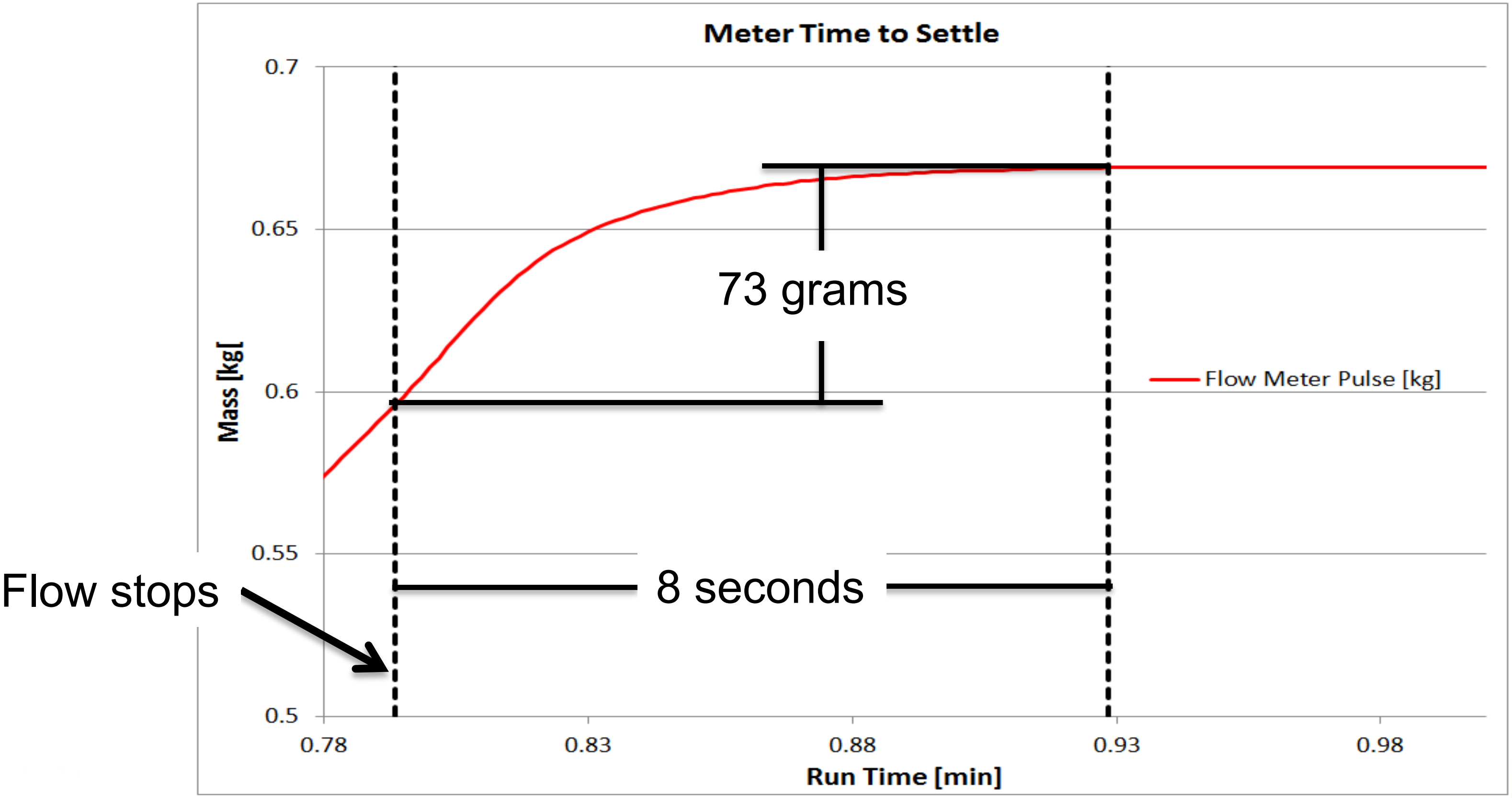
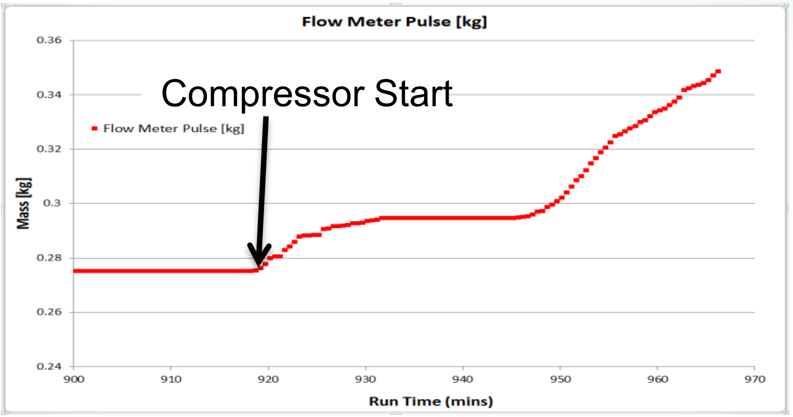
Accomplishment: Meter Delay

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

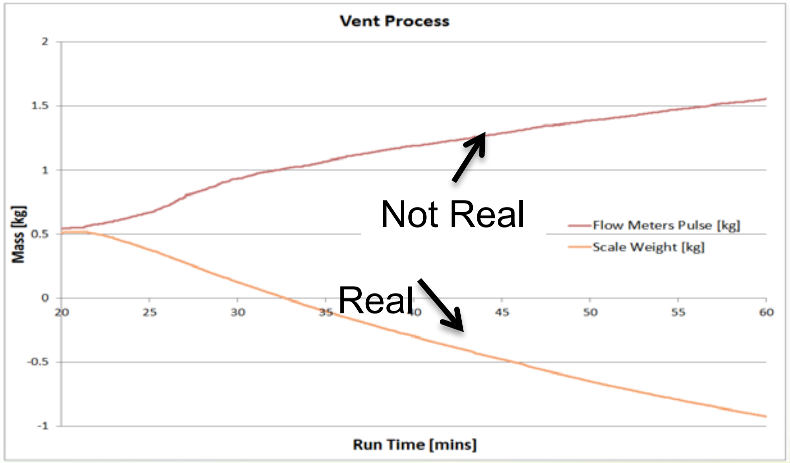


Accomplishment: Vibration

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



False readings of a Coriolis meter from nearby venting



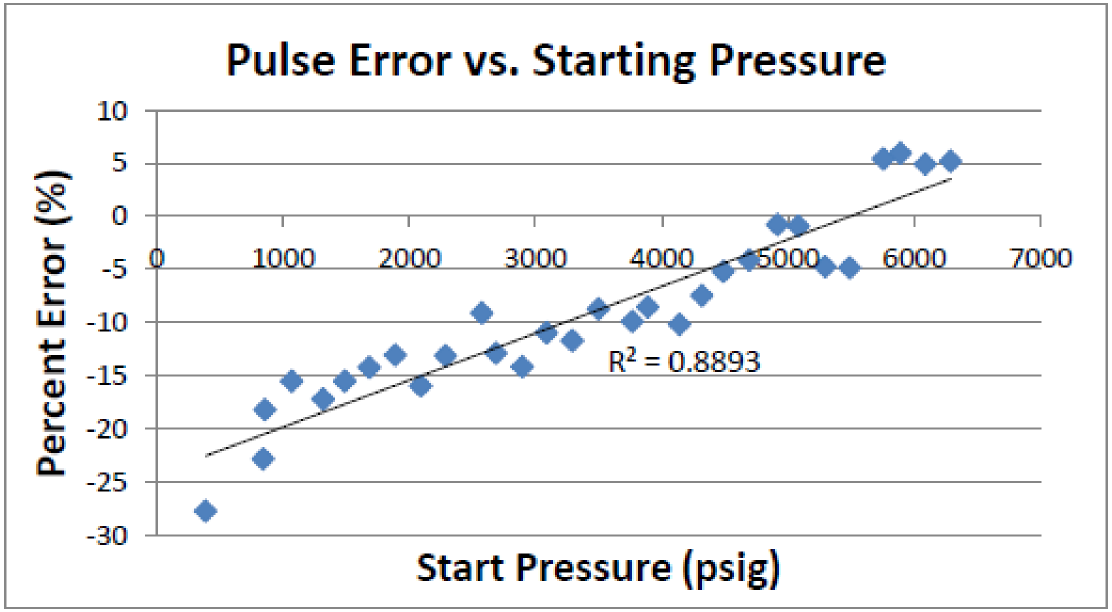
Accomplishment: Pulse Testing

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



Responses to Reviewer Comments

It is important to advance an accurate and reliable way of measuring hydrogen at stations. However, the goals of this project do not seem to be well defined. It is not clear whether the goal is to improve accuracy of existing flow meters or to compare/validate the performance of commercial meters or to develop a protocol for testing the accuracy of hydrogen flow meters. Also, some of the stated barriers do not appear to be addressed by this project, at least not at this stage.

The goal of the project is to measure and benchmark flow meter performance as they would be used in the field. This benchmarking includes guidance on how to install flow meters in a dispenser and identification of other factors that may affect flow meter performance. It is not a goal of the project to develop a protocol for testing the accuracy of hydrogen flow meters or to improve performance of flow meters themselves, although, it is the hope that manufactures can use this data to improve their designs.

While the low tolerances are certainly a technical challenge, it would be going too far to say they are “impeding” the sale of hydrogen, as there are (temporary) countermeasures to address this issue in the near term. There are not clear reasons to look at meters that are not in practice/use at stations. It seems that it would be more relevant to use actual meters that are in service and help improve those. A separate project can be initiated to look at potential metering technology.

The temporary countermeasures expire in 2018 and 2020, so flow meters need to be fully compliant by then. Two of the flow meters tested are “field meters”, while the third meter we tested has a significantly lower price point than the other two meters.

Collaboration

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 and procurement process. Developmental meters have been identified for continued testing.

State Metrologist

- California Division of Measurement Standards was consulted to utilize field data from dispenser certification.
- Working with northeast station developers 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.

Challenges and Barriers

- Reporting challenges while maintaining confidential information
- Changing targets for flow meter performance
- Meter R&D is limited by near term market potential
- Resources for future testing to support meter manufacturers and codes/standards

Proposed Future Work

Next phase

- Test more commercial or prototype meters
- Test meters in pre-chilled section of the dispenser
- Develop a controls scheme based on meter performance to improve accuracy in the field
- Help with new device to serve stations in Northeast U.S.

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

Technology Transfer Activities

- Prototype flow meter testing
  - Work with companies that have meters in development and perform baseline testing
- Share data with station operators
  - Problem of data sharing while maintaining confidentiality

Summary

Relevance:
- Hydrogen meters are currently meeting accuracy class 5.0 in the field
- All relaxed accuracy classes will sunset in 2020

Approach:
- Design and build laboratory grade gravimetric hydrogen standard
- Conduct high pressure hydrogen testing of commercially available flow meters

Technical Accomplishments:
- 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

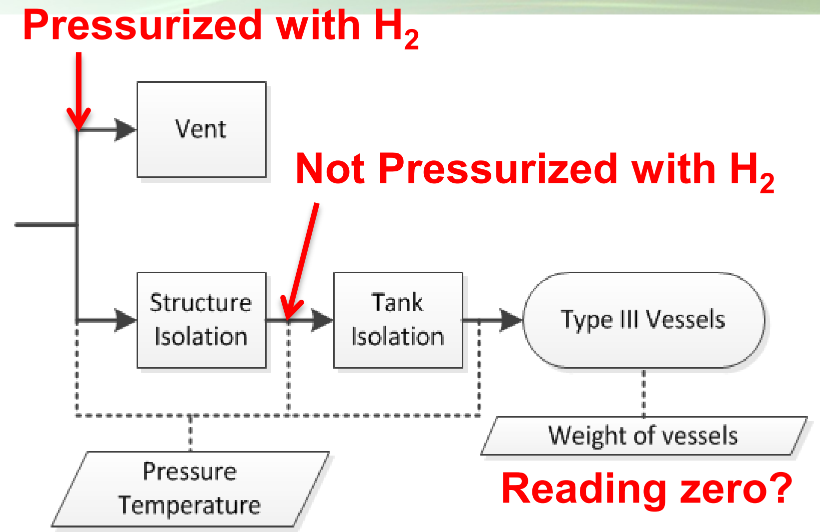
Proposed Future Research:
- Test more commercial or prototype meters
- Develop a controls scheme to improve meter performance in the field

Technical Back-Up Slides

Accomplishment: Pre-Testing of System

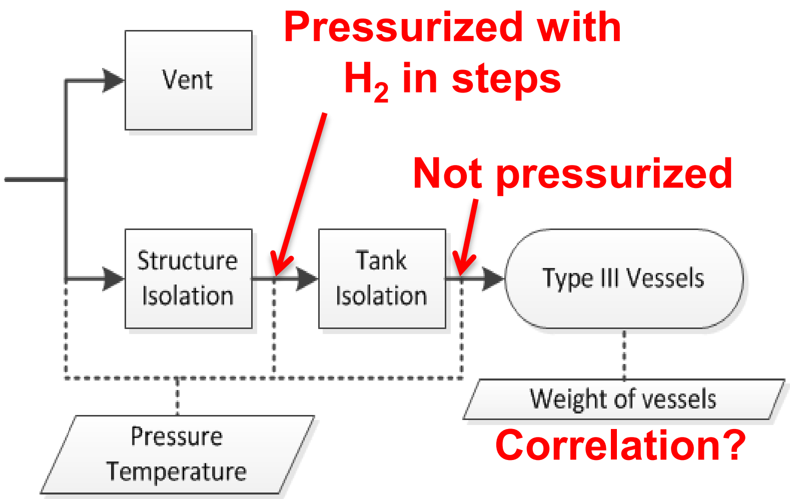
Outer & inner structure interaction

- Confirm separation between the outer and inner structure
- Pressurize lines up to isolation valve separating inner and outer structure and confirm zero readout on scale when pressurized



Slow & fast step up of hydrogen

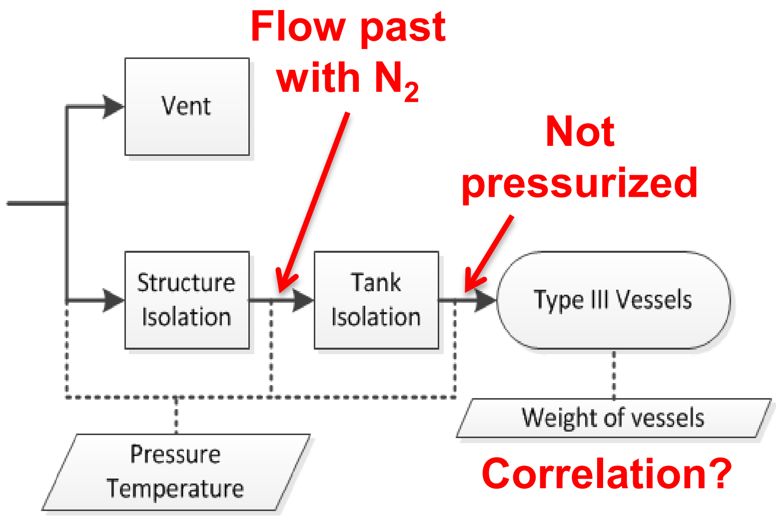
- Step up pressure in hydrogen lines up to vessels and compare static scale reading to PVT estimate
- Establish correlation between PVT estimate and scale reading under static conditions



Accomplishment: Pre-Testing of System

Flow on gravimetric measurement

- Effects of flow on scale reading to explore if real time flow measurements is plausible
- Flow past vessel isolation valves and determine correlation between flow and scale reading


Flow past with N_2

Not pressurized

Vent

Structure Isolation

Tank Isolation

Type III Vessels

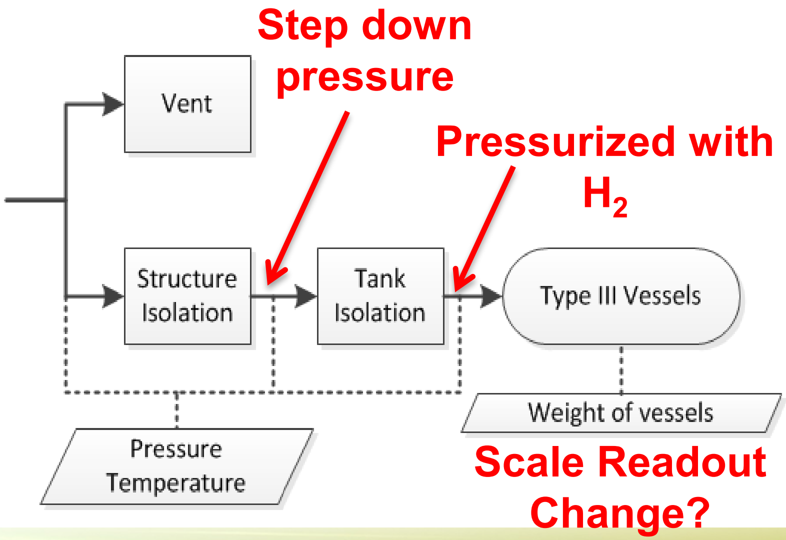
Weight of vessels

Pressure Temperature

Correlation?

Step Down

- Effects of depressurizing fill lines on the weighing scale
- Fill the hydrogen vessels and record the scale readout, slowly step down pressure in lines will maintaining hydrogen in vessels


Step down pressure

Pressurized with H_2

Vent

Structure Isolation

Tank Isolation

Type III Vessels

Weight of vessels

Pressure Temperature

Scale Readout Change?

System measurement error

To compare the meter to our system we need to include a system PVT adjustment and a scale adjustment based on pressure, so what is the system error?

system error = sqrt(scale error^2 + scale adjustment error^2 + PVT adjustment error^2)

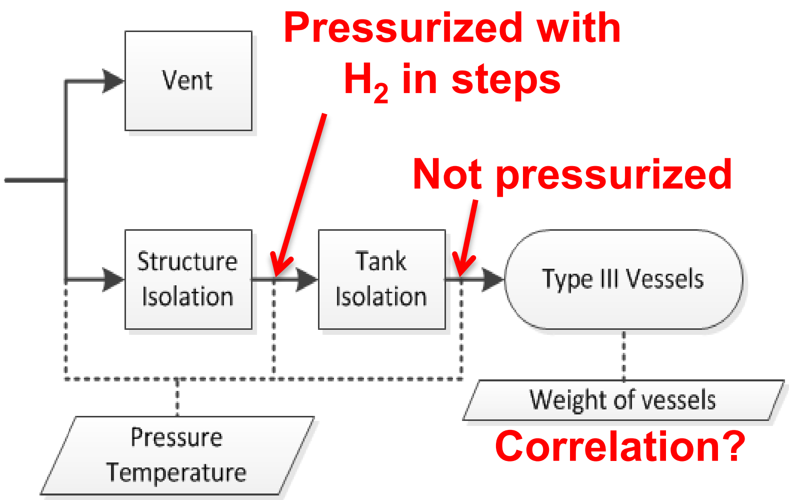
Scale error – Checked periodically
PVT adjustment error – Calculated with formula
Scale adjustment error – Cannot calculate

Pre-testing of system

Slow & fast step up of hydrogen

- Step up pressure in hydrogen lines up to vessels and compare static scale reading to PVT estimate
- Establish correlation between PVT estimate and scale reading
- Linear relationship that was consistent regardless of slow or fast steps, size of steps, or starting pressure

Worst case this estimate is 10% off so we put Scale Adjustment Error = 2 grams



Pressurized with H_2 in steps

Not pressurized

Vent

Structure Isolation

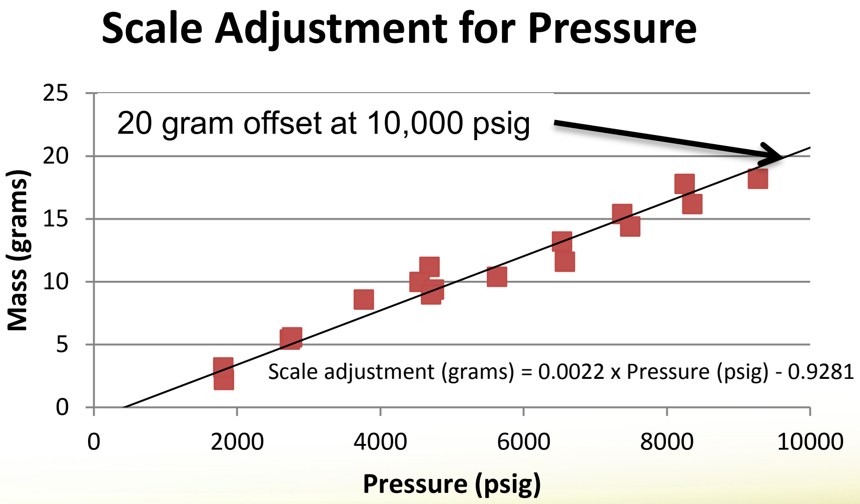
Tank Isolation

Type III Vessels

Weight of vessels

Pressure Temperature

Correlation?



Scale error

Scale error = FW_{ZE} + FW_{LE} + IE

Where

FW_{ZE} = Fractional weight amount used at zero (Zero Error)
FW_{LE} = Fractional weight amount used at 2 kg (Load Error)
IE = Indication error with load on (Indication – 2 kg)

Checked periodically and tracked

± 1.5 grams (worst case)

PVT adjustment error

The Assumptions and Errors

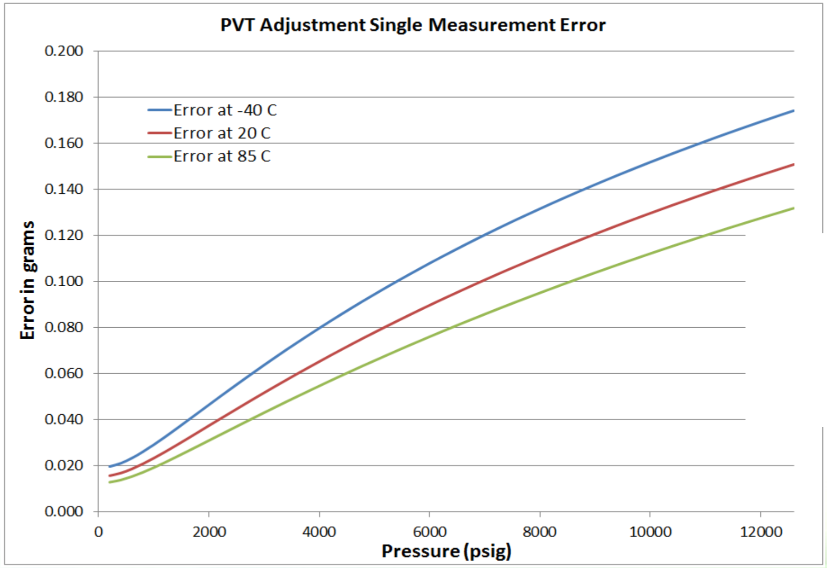
- R & M do not have error associated with them
- Pressure error = 0.25% of F.S.
- Temperature error = 1°C
- Volume error = 5% of total
- z error = 0.01% (NIST)

The Formulas

$$m = \frac{M * V * P}{z * T * R}$$

$$\delta m = \sqrt{\left(\frac{dm}{dV}\right)^2 * (\delta V)^2 + \left(\frac{dm}{dP}\right)^2 * (\delta P)^2 + \left(\frac{dm}{dT}\right)^2 * (\delta T)^2 + \left(\frac{dm}{dz}\right)^2 * (\delta z)^2}$$

$$\delta m = \sqrt{\left(\frac{M * P}{z * T * R}\right)^2 * (\delta V)^2 + \left(\frac{M * V}{z * T * R}\right)^2 * (\delta P)^2 + \left(\frac{-M * V * P}{z * T^2 * R}\right)^2 * (\delta T)^2 + \left(\frac{-M * V * P}{z^2 * T * R}\right)^2 * (\delta z)^2}$$



Calculated
± 0.18 grams
(worst case)

The Constants

R = 8.314 kJ / (K kmol)

M = 2.0158 kg / kmol

System measurement error

To compare the meter to our system we need to include a system PVT adjustment and a scale adjustment based on pressure, so what is the system error?

system error = sqrt(scale error^2 + scale adjustment error^2 + PVT adjustment error^2)

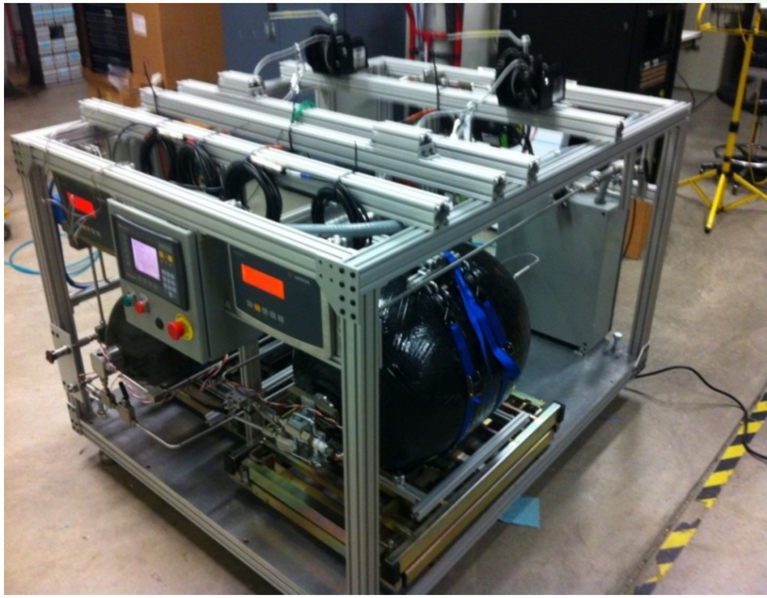
Worst Case

$$SE = \sqrt{1.5^2 + 2^2 + 0.18^2}$$

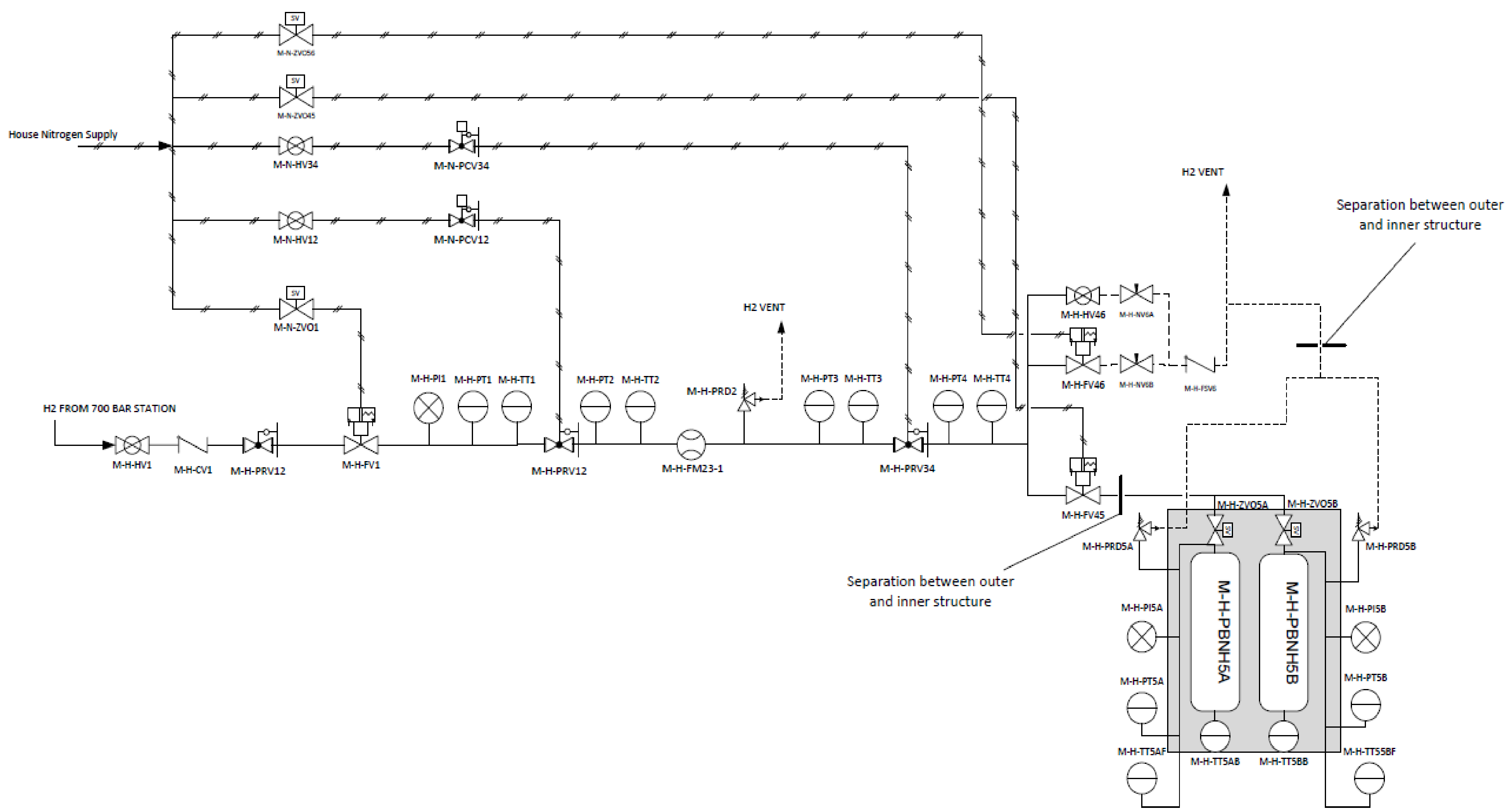
System Error (worst case) = 2.5 grams

Relevance: California Station Metrology

- NREL hydrogen metrology standard is being used by California DMS for permitting hydrogen stations (contracted through CEC funding)
- Station metrology testing by California DMS is being conducted to facilitate the sale of hydrogen as a motor vehicle fuel
- NIST Handbook 44 requirements for ± 1.5% accuracy are adopted by California Code of Regulations (CCR)
- CCR has been amended to add temporary relaxed accuracy classes of 3%, 5% and 10%



Piping and Instrumentation Diagram



Acronyms and Abbreviations

AIST: National Institute of Advanced Industrial Science and Technology

CARB : California Air Resources Board

CCR: California Code of Regulations

CDFA: California Department of Food and Agriculture

CEC : California Energy Commission

DMS : Division of Measurement Services

DUT : Device Under Test

ESIF : Energy Systems Integration Facility

GUI : Graphic User Interface

HySUT: The Research Association of Hydrogen Supply/Utilization Technology

IET : Institute for Energy and Transport

JRC: Joint Research Centre

MPa : Mega-Pascal

NIST: National Institute of Standards and Technology

PLC : Programmable Logic Controller

SAE: Society of Automotive Engineers

SNL: Sandia National Laboratories