NREL
NATIONAL RENEWABLE ENERGY LABORATORY

How Advanced Hydrogen Fueling Protocols can Improve Fueling Performance & H_2 Station Design

Steve Mathison

Hydrogen Production, Power, and Storage

Center for Integrated Mobility Services

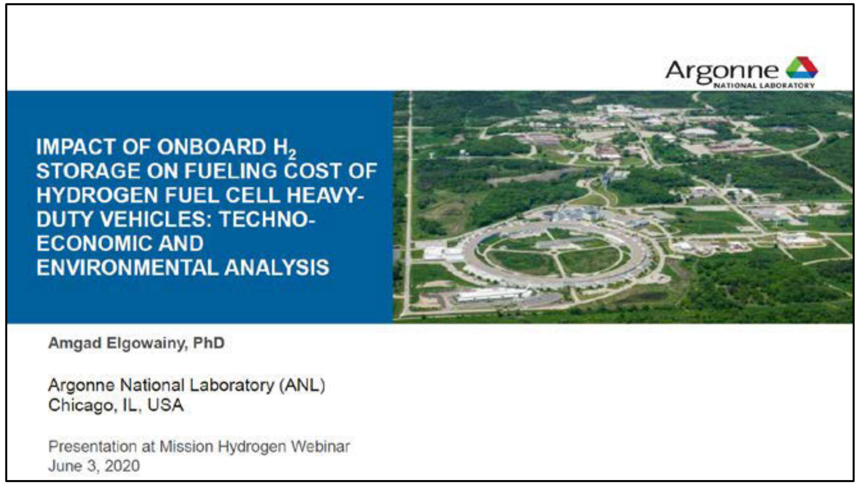
Presented at Mission Hydrogen Webinar

July 15, 2020

NREL/PR-5400-77368

How to Optimize Hydrogen Refueling Stations

Part 1: June 3rd Webinar (Dr. Elgowainy)



- Excellent **big picture assessment** with **longer term outlook**
- Focused on impacts of on-board storage and gaseous vs liquid H_2 stations
- Analysis **focused on HD vehicles and infrastructure**

Part 2: Today's Webinar

- **Nearer term** & focused on **today's compressed H_2 storage systems**
- Focused on **impacts** of the **hydrogen fueling protocol** on **fueling performance** and **H_2 station design**
- Analysis **is applicable to both HD & LD vehicles** and **infrastructure**

U.S. DOE EERE – HD Long-Haul FC Truck Targets

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Hydrogen and Fuel Cell Technologies Office

- Published Technical Targets for Long-Haul Heavy-Duty Fuel Cell Trucks in October 2019 *
  - Fast Fueling → 10 kg/min ultimate
  - Long Range → 750 miles ultimate

- Technologies needs to achieve targets:
  - a) High Flow HD Fueling Components
  - b) Optimal H_2 Fueling Protocols

3 Target Tables for Hydrogen Fueled Long-Haul Trucks

Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	**25,000**	**30,000**
Fuel Cell System Cost[1,3,4]	\$/kW	**80**	**60**
Fuel Cell Efficiency (peak)	%	**68**	**72**
Hydrogen Fill Rate	kg H_2/min	**8**	**10**
Storage System Cycle Life[5]	cycles	**5,000**	**5,000**
Pressurized Storage System Cycle Life[6]	cycles	**11,000**	**11,000**
Hydrogen Storage System Cost[4,7,8]	\$/kWh (\$/kg H_2 stored)	**9 (300)**	**8 (266)**

5.5 Hydrogen Long-Haul Truck Range

Table 10. Long-Haul Range for Hydrogen Trucks, Interim and Ultimate Assumptions

	Status Estimate	Tractor-Trailer Trucks	
		Interim	Ultimate
Vehicle Range [miles]	**300[1]**	**600**	**750**

1 Based on Toyota Project Portal for drayage applications.

* https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

NREL at a Glance

2,307

Employees,
plus more than
460
early-career researchers
and visiting scientists

World-class
facilities, renowned
technology experts

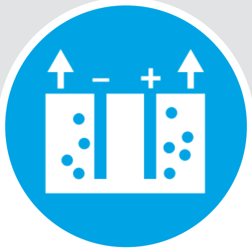
about 900

Partnerships
with industry,
academia, and
government

Campus
operates as a
living laboratory

Key FCHT Research Areas

Program Key Areas Strategy Summary:
Over the next five years, NREL's efforts will improve the economic viability of transforming, transporting, and storing hydrogen technologies in conjunction with key government and industry partners who will accelerate their adoption



Make

- Electrochemical
- Photoelectrochemical
- Biological
- Thermochemical
- Grid integration
- Power electronics
- Direct connect renewable integration

Move

- Pressure
- Form
- Quantity
- Mode

Store

- On-board
- Carriers
- Bulk

Use

- Fuel cells
- Electrons to Molecules
- Fuel upgrading*
- Combustion*
- Metal reductant*

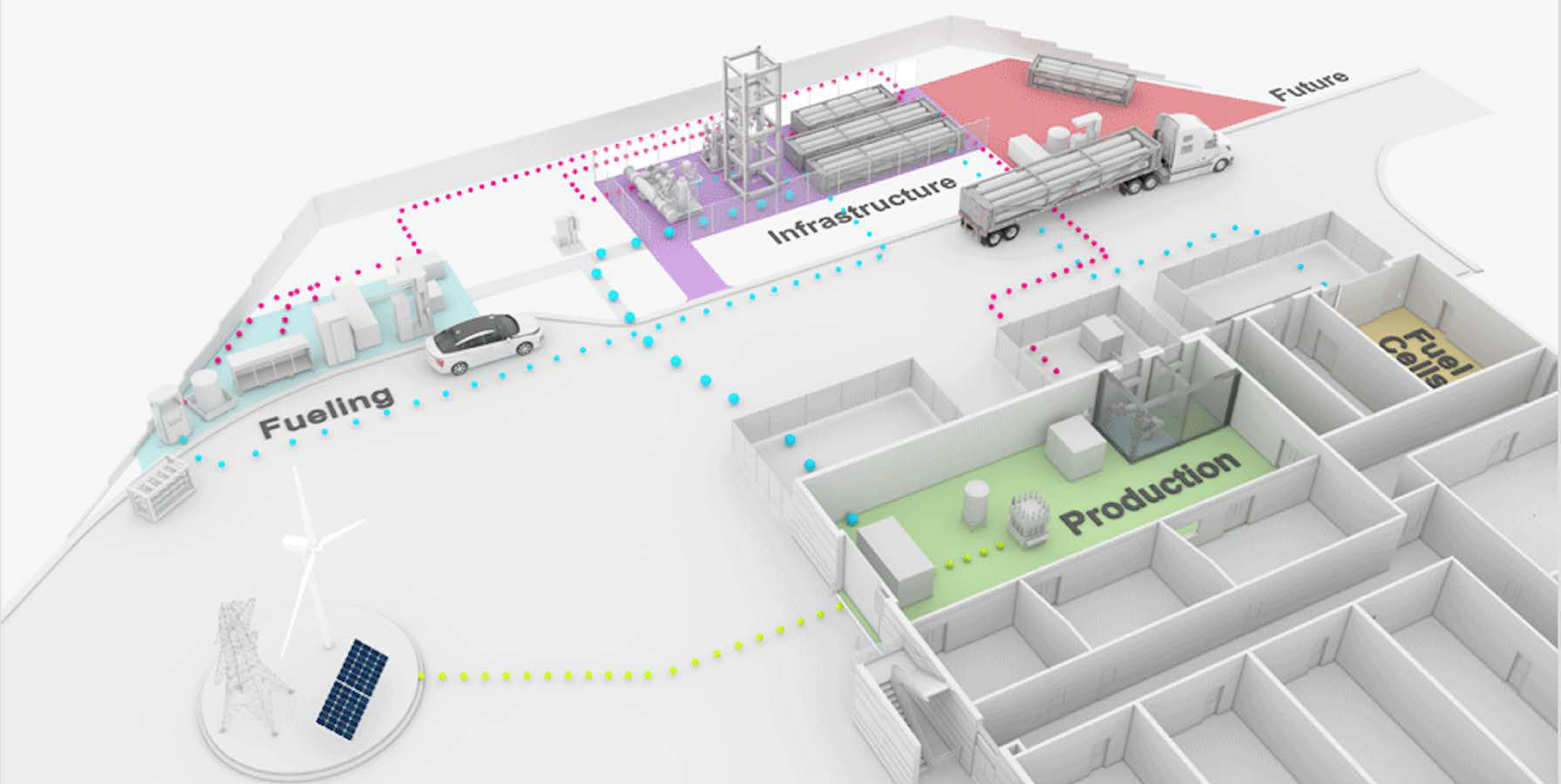
Crosscuts

- Foundational decision science
- Manufacturing
- Safety
- People

*future

Vision: *Hydrogen will be a ubiquitous means of transporting, storing, and transforming energy at the scale necessary to enable a clean and vibrant economy*

NREL's H_2 Systems Experimental Capabilities



“Innovating Hydrogen Stations” Research Project

Advance hydrogen station capabilities

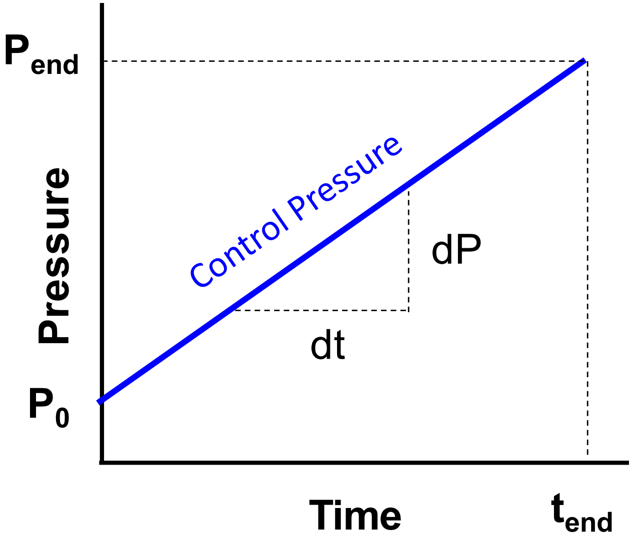
DOE HFTO funded H2@Scale CRADA Project with Industry Partners: Shell, Air Liquide, Toyota, Honda

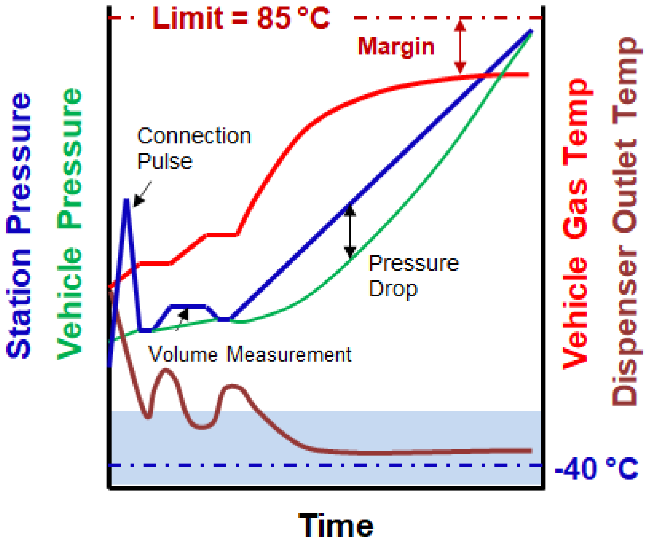
A research and industry partnership for an experimentally validated high flow rate fueling model and near-term hydrogen station innovations that benefits multiple markets and stakeholders

Fueling Protocol Overview

What is a fueling protocol?

- ➢ A **set of procedures** that dictate the **process** which a **station follows** to **safely fuel** a compressed hydrogen storage system (CHSS)





Fueling Protocol Standard

SAE INTERNATIONAL

J2601

"Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles"

Most Recent Publication – May 2020

US

Currently No Federal Regulation

All public stations utilize J2601

EU

EN 17127
"Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols"

References J2601

JPN

Regulation - JPEC S-0003

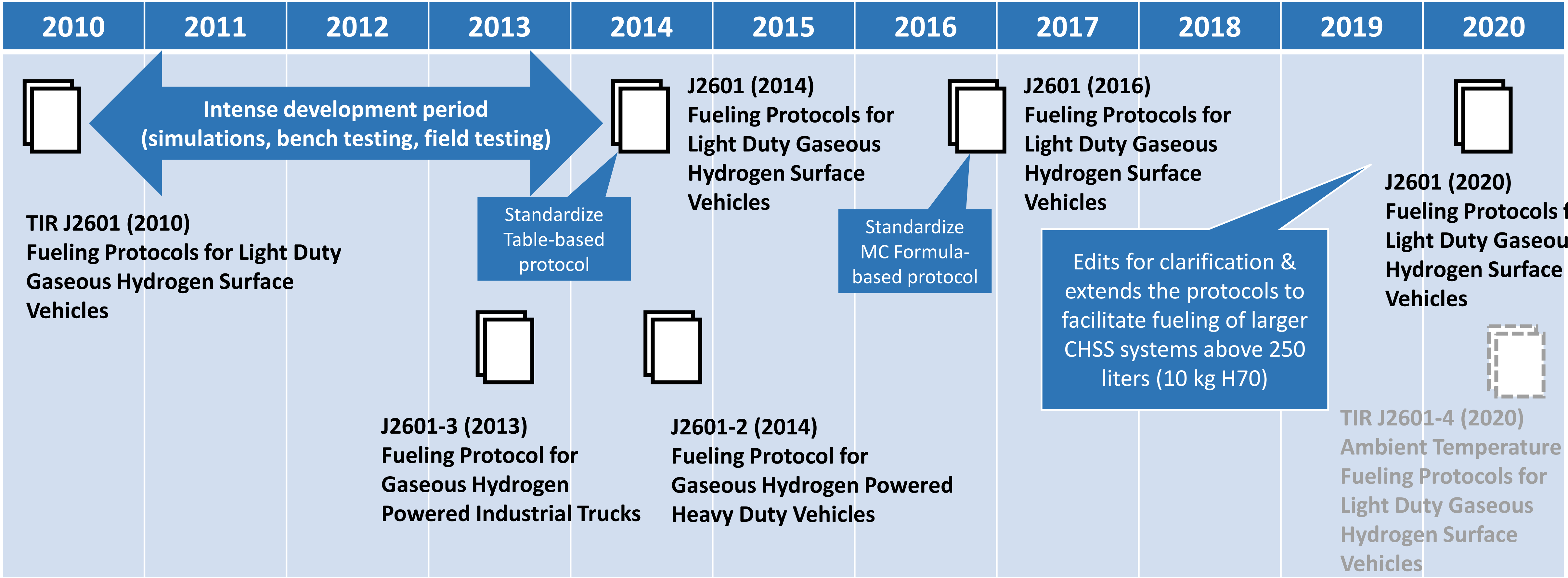
Based on SAE J2601

Why is a fueling protocol needed?

- ➢ To **ensure** that the CHSS **stays within its operational boundaries** (pressure and temperature)
- ➢ A fueling protocol can dictate the **fueling speed** ($\frac{dP}{dt}$, t_{end}) & **end pressure** P_{end}

- Currently, SAE J2601 is the worldwide recognized fueling protocol standard for light duty fueling
- A new revision to J2601 was just published in May 2020 -- https://saemobilus.sae.org/content/J2601_202005/

History of SAE H_2 Fueling Protocols



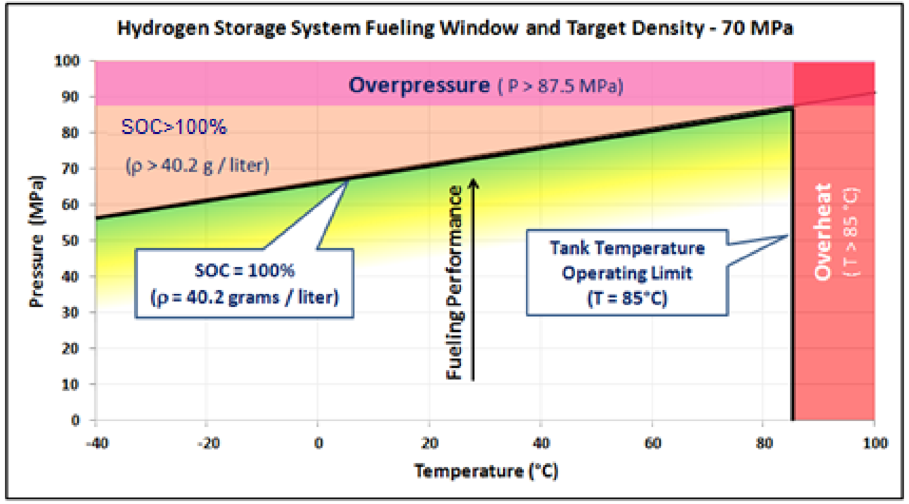
- There are a family of SAE J2601 fueling protocol standards to address the needs of light duty, H35 heavy duty, and forklifts
- Current SAE ITF activities aim to standardize a high flow fueling protocol for HD vehicles in conjunction with the ISO.

SAE J2601 Philosophy

Philosophy for SAE J2601 Fueling Protocols:

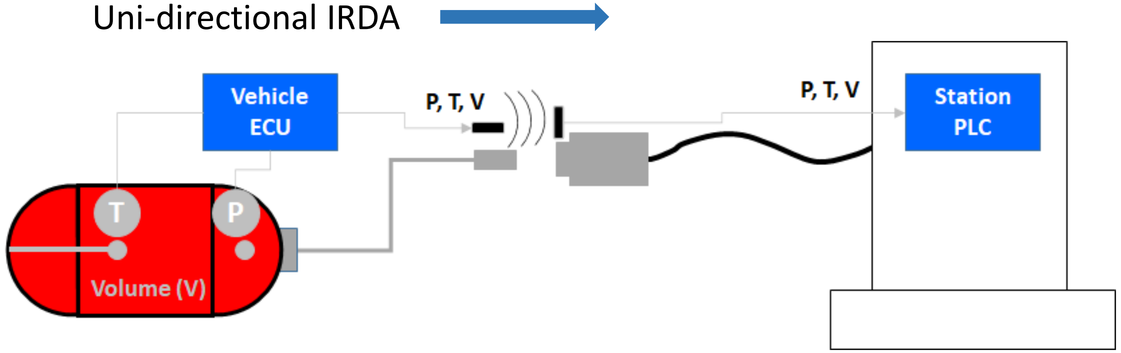
- <u>H_2 Station is fully responsible for safe fueling of the vehicle</u>
- No safety critical information from vehicle is used *
- Worst case boundary conditions are assumed

Storage Vessel Operational Window **



*** Figure 3 from 2020 version of SAE J2601*

Fueling Can be Conducted With or Without Communications



* Communicated data is not used for **safety related functions** – it is **only used for fill quality**

- The current SAE J2601 is based on this philosophy which dictates the higher level structure of the fueling protocols
- This philosophy was chosen after much discussion in the SAE ITF

J2601 Protocol Structures

Table-base Protocol

Inputs

Vehicle Parameters
- Initial Gas Pressure

Station Parameters
- Ambient Temp.
- Delivered Gas Temp.

Boundary

Fuel Temperature (T40 = -40 °C)

SAE J2601 Lookup Tables *

H70-T40 4-7kg non-comm

Target Pressure, P_{target} — **Initial pressure** — Initial Tank Pressure, P_0 [MPa]

Ambient Temperature, T_{amb} [°C]	Average Pressure Ramp Rate, APRR [MPa/min]	0.5	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	5.1	77.8	77.6	77.3	76.9	76.6	[illegible]	[illegible]	[illegible]	[illegible]	73.9	72.8	no fueling
45	8.1	76.3	77.2	76.9	76.5	76.4	76	[illegible]	[illegible]	[illegible]	73.9	72.7	no fueling
40	11.5	73.2	75.6	76.8	76.3	76.4	76	[illegible]	[illegible]	[illegible]	73.9	72.7	no fueling
35	12.4	72.9	75.3	76.4	76.0	76.1	75	[illegible]	[illegible]	[illegible]	73.8	72.7	no fueling
30	15.3	[illegible]	73.9	75.8	75.2	75.4	75	[illegible]	[illegible]	[illegible]	72.4	71.3	no fueling
25	18.5	69.0	[illegible]	75.1	74.5	74.7	74.3	73.3	73.0	72.0	71.1	no fueling	no fueling
20	21.8	67.9	72.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	71.9	70.7	69.7	no fueling	no fueling
10	28.0	66.3	71.1	74.1	[illegible]	[illegible]	[illegible]	[illegible]	69.6	68.4	66.9	no fueling	no fueling
[illegible]	[illegible]	[illegible]	[illegible]	72.4	[illegible]	[illegible]	[illegible]	[illegible]	67.1	65.7	64.0	no fueling	no fueling
[illegible]	[illegible]	[illegible]	[illegible]	71.9	[illegible]	[illegible]	[illegible]	[illegible]	64.4	62.9	61.2	no fueling	no fueling
[illegible]	[illegible]	[illegible]	[illegible]	71.3	[illegible]	[illegible]	[illegible]	[illegible]	62.4	60.0	no fueling	no fueling	no fueling
[illegible]	[illegible]	[illegible]	[illegible]	70.6	70.4	69.0	67.4	65.2	61.8	58.7	no fueling	no fueling	no fueling
[illegible]	[illegible]	[illegible]	[illegible]	70.2	70.0	68.5	66.9	64.8	61.5	58.5	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Callouts: **Pressure Target**, **Pressure Ramp Rate**, **Ambient Temp**

Outputs
- Ending Pressure
- Constant Pressure Ramp Rate

** Table D-25 from 2016 version of SAE J2601*

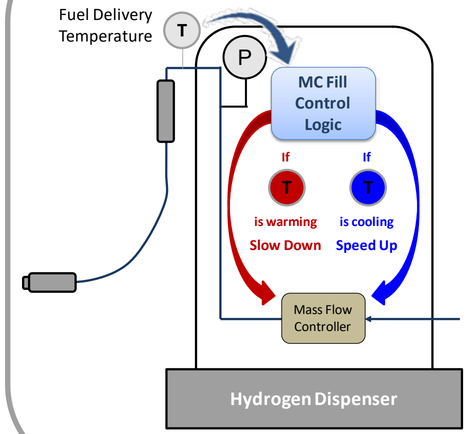
Refueling Control is *Static*

MC Formula Protocol

Inputs

Vehicle Parameters
- Initial Gas Pressure

Station Parameters
- Ambient Temp.
- Delivered Gas Temp.
- Delivered Gas Press.



Calculate Mass Ave T → MAP → **Pressure Ramp Rate**

Calculate Mass Ave *h* →

$$T_{final} = \frac{m_2 C_v T_{adiabatic} + MC T_{initial}}{MC + m_2 C_v}$$

MC* Method → **Pressure Target**

Outputs
- Ending Pressure
- Variable Pressure Ramp Rate

Refueling Control is *Dynamic*

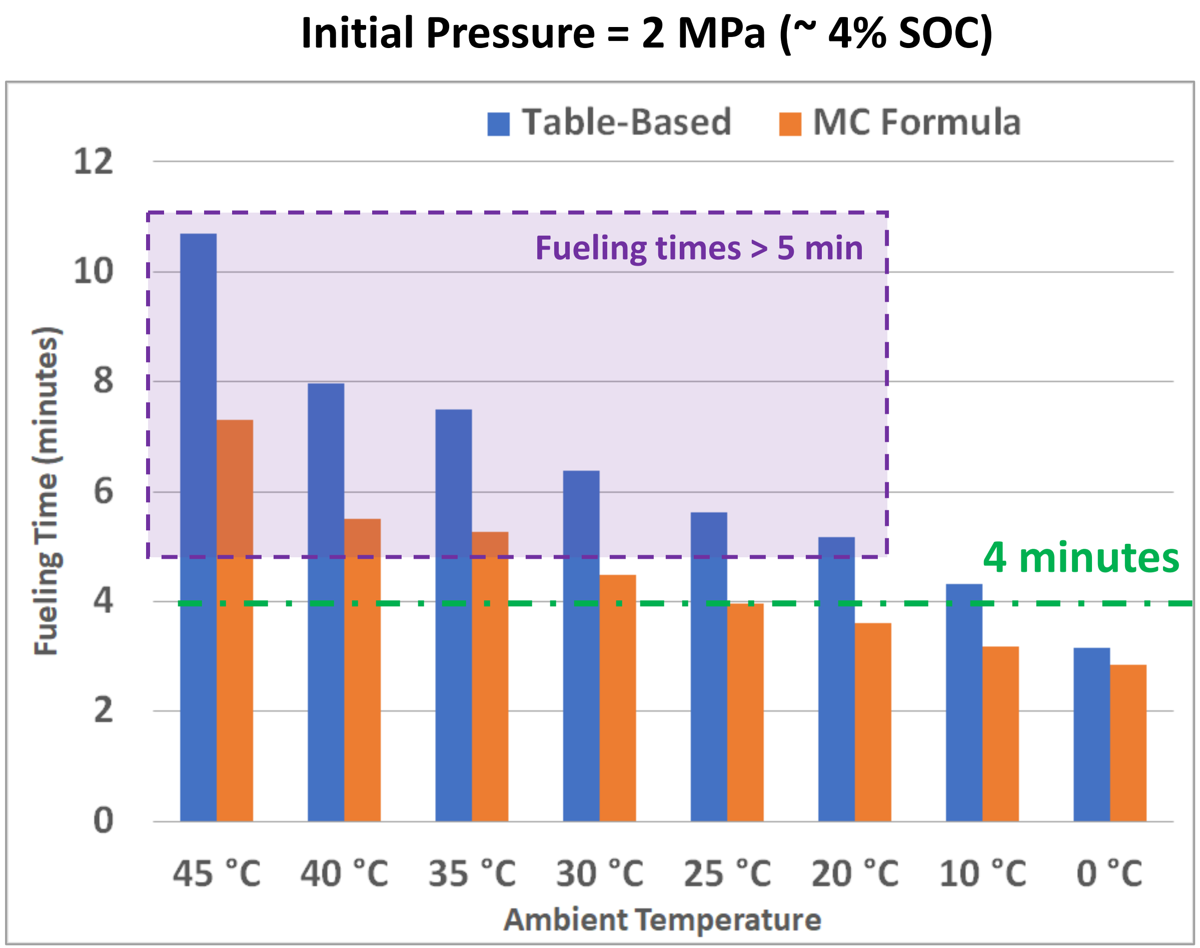
** MC Method is a lumped heat capacitance model that calculates end of fill gas temp*

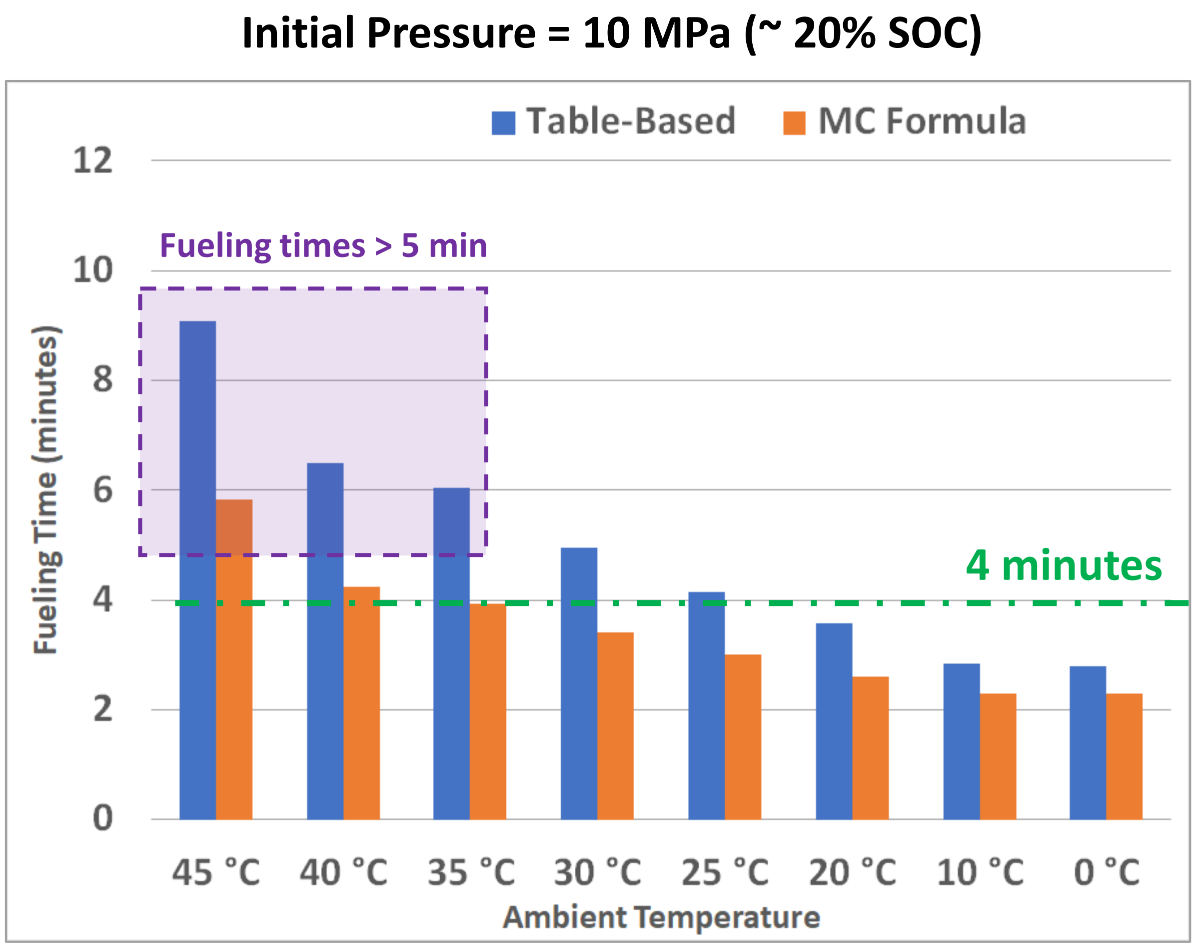
"MC" denotes the heat capacity of the tank system

$m_{(kg)} \times C_{(J/kgK)}$

- MC Formula uses feedforward control to dynamically adapt to actual fueling conditions
- Table-based protocol uses static control based on an assumed range of fuel delivery temperatures (i.e. T40, T30, T20)

Fueling Performance - Potential

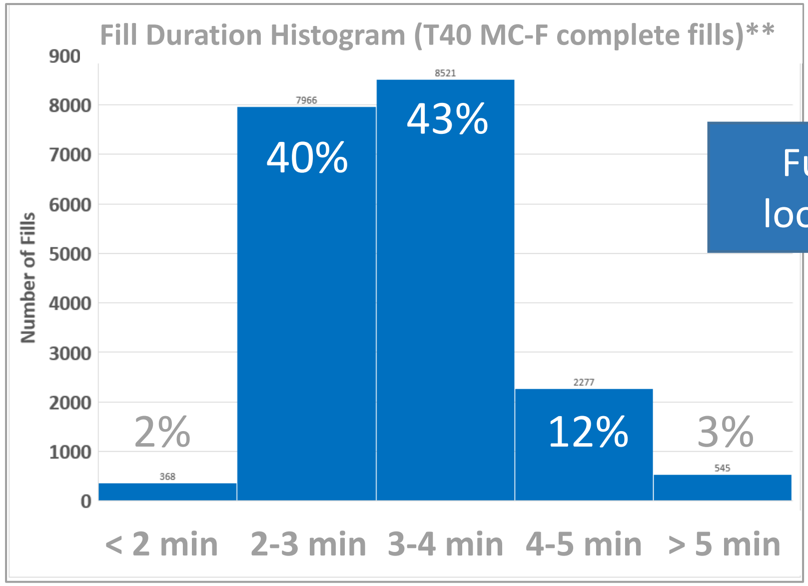




Assumptions → 2020 SAE J2601 Standard, Vehicle CHSS size = 122.4 L (Toyota Mirai), Fuel Delivery Temperature = -36 °C, End of Fill SOC = 98%

- **The MC Formula fueling protocol is currently the state-of-the-art**
- **With sufficiently cold pre-cooling temperatures, the majority of fills take less than 4 minutes**

J2601 Real World Fueling Data (35,000 + MC-F fills*)



* Thank you to Joe Cohen and Air Products for providing this data

** Complete fills means ≥ 95% SOC

Fueling Times look reasonable

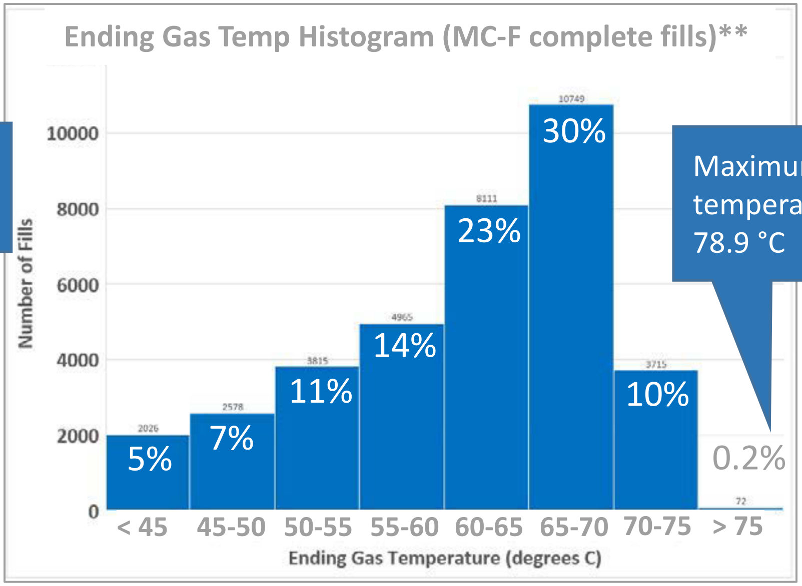
97% < 5 min

85% < 4 min

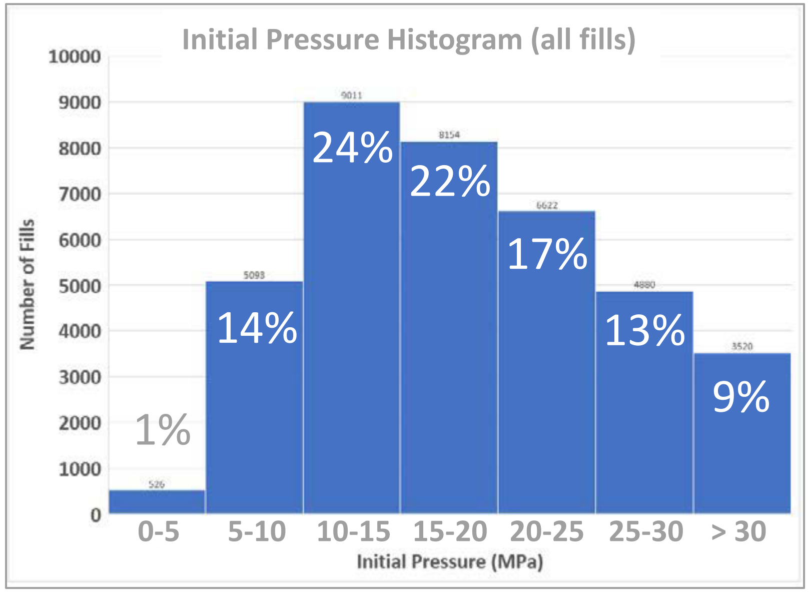
Ending Gas Temps well below 85 °C

99.8% < 75 °C

90% < 70 °C



Maximum gas temperature = 78.9 °C



1% < 5 MPa

15% < 10 MPa

39% < 15 MPa

61% < 20 MPa

- ❑ **Current J2601 Protocols are conservative and have much unused margin**
- ❑ **Margin = difference between ending gas temperature and the gas temperature limit of 85 °C**
  - **99.8%** of fills have **margin > 10 °C**
  - **90%** of fills have **margin > 15 °C**

- T40 fueling times look to be acceptable. Ending gas temperatures show quite a bit of margin below 85 °C limit

How can fueling protocols be improved?

- **Develop approaches which can reduce the gas temperature margin**

Current

Pre-cool Temperature

-33 °C

Gas Temperature Margin

~ 10 °C

Fueling Time

97% <
5 min

How can fueling protocols be improved?

- **Develop approaches which can reduce the gas temperature margin**

Current	**Faster Fueling ***
Pre-cool Temperature: **-33 °C**	Pre-cool Temperature: **-33 °C**
Gas Temperature Margin: **~ 10 °C**	**Gas Temperature Margin**: ↓ **5 °C**
Fueling Time: **97% < 5 min**	**Fueling Time**: ↓ **97% < 3 min**

*** High throughput stations**

How can fueling protocols be improved?

❖ **Develop approaches which can reduce the gas temperature margin**

Current

Pre-cool Temperature

-33 °C

Gas Temperature Margin

~ 10 °C

Fueling Time

97% < 5 min

Faster Fueling *

Pre-cool Temperature

-33 °C

Gas Temperature Margin

↓ **5 °C**

Fueling Time

↓ **97% < 3 min**

*** High throughput stations**

Warmer Pre-cooling **

Pre-cool Temperature

↓ **-25 °C**

**** Reduced energy & costs**

Gas Temperature Margin

↓ **5 °C**

Fueling Time

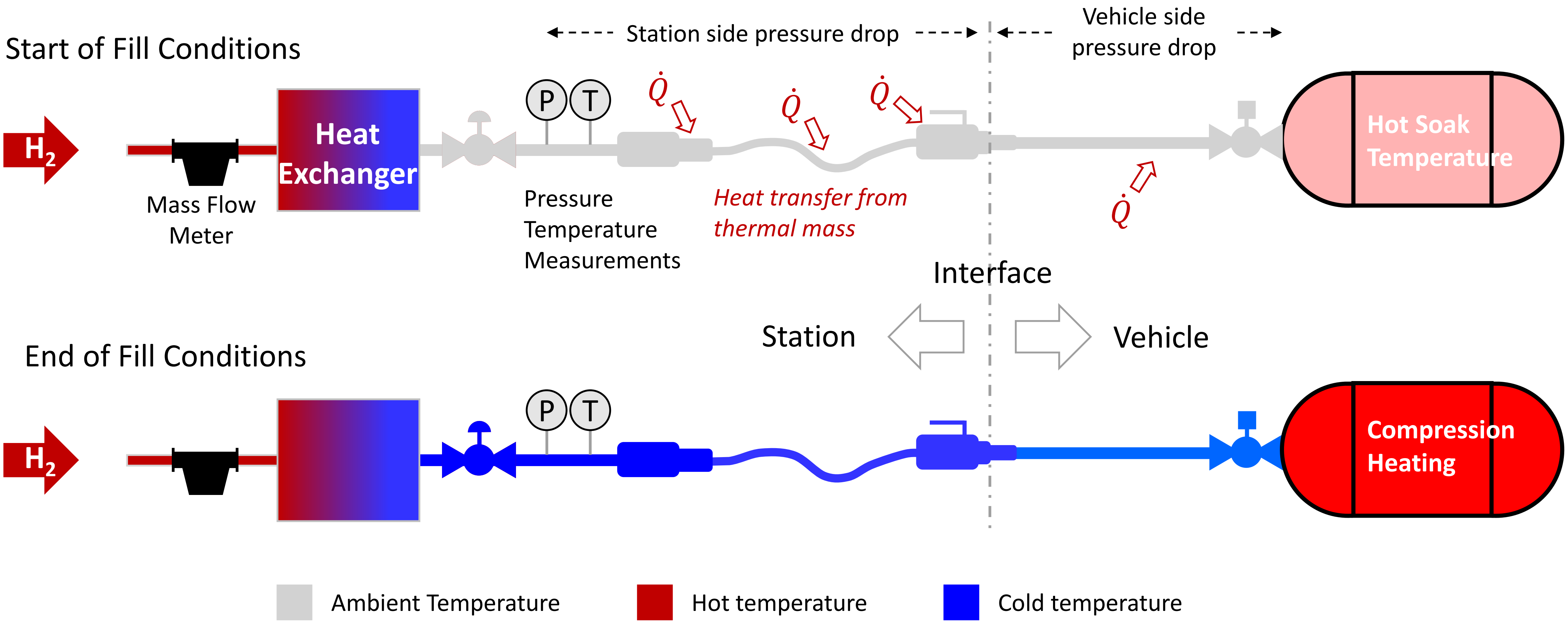
97% < 5 min

Where does the margin come from?

SAE J2601 Worst Case Assumptions

Diagram of Fueling Elements Which Influence the Protocol

- A set of **worst-case assumptions** are made for these elements
- <u>The protocols are based on **all these assumptions being true at the same time**</u>



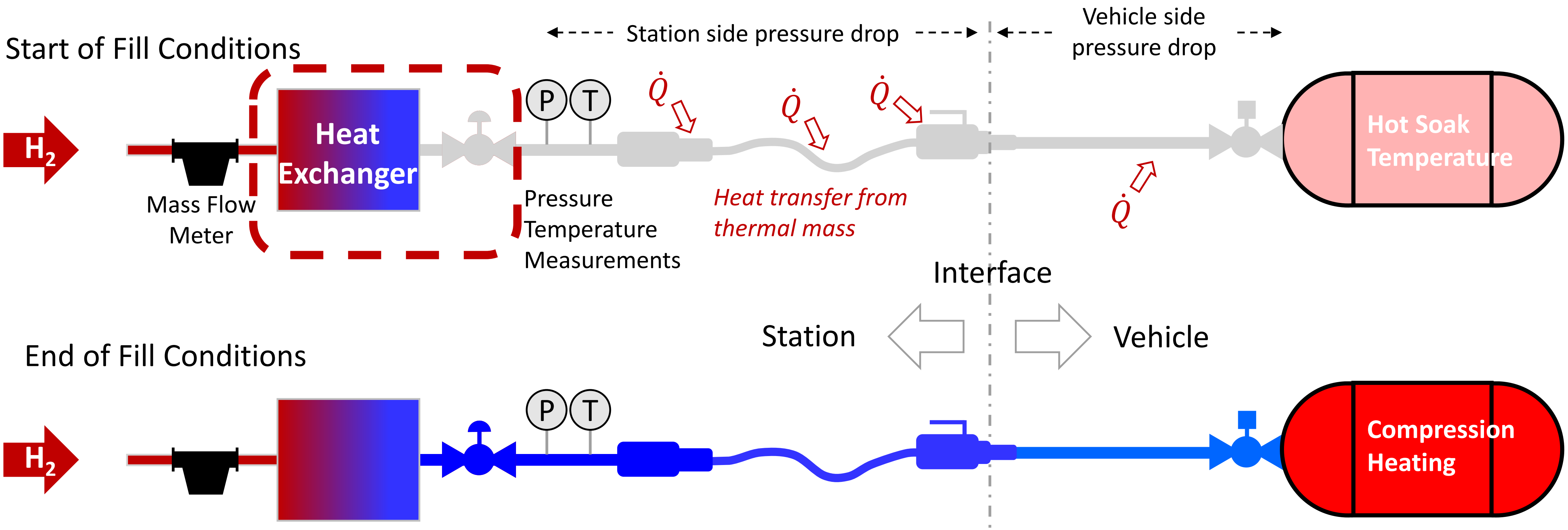
Where does the margin come from?

SAE J2601 Worst Case Assumptions

Pre-cooling assumptions

Fuel delivery temperature is at an upper boundary value* (e.g. -33 °C for T40)

** not applicable to MC Formula*



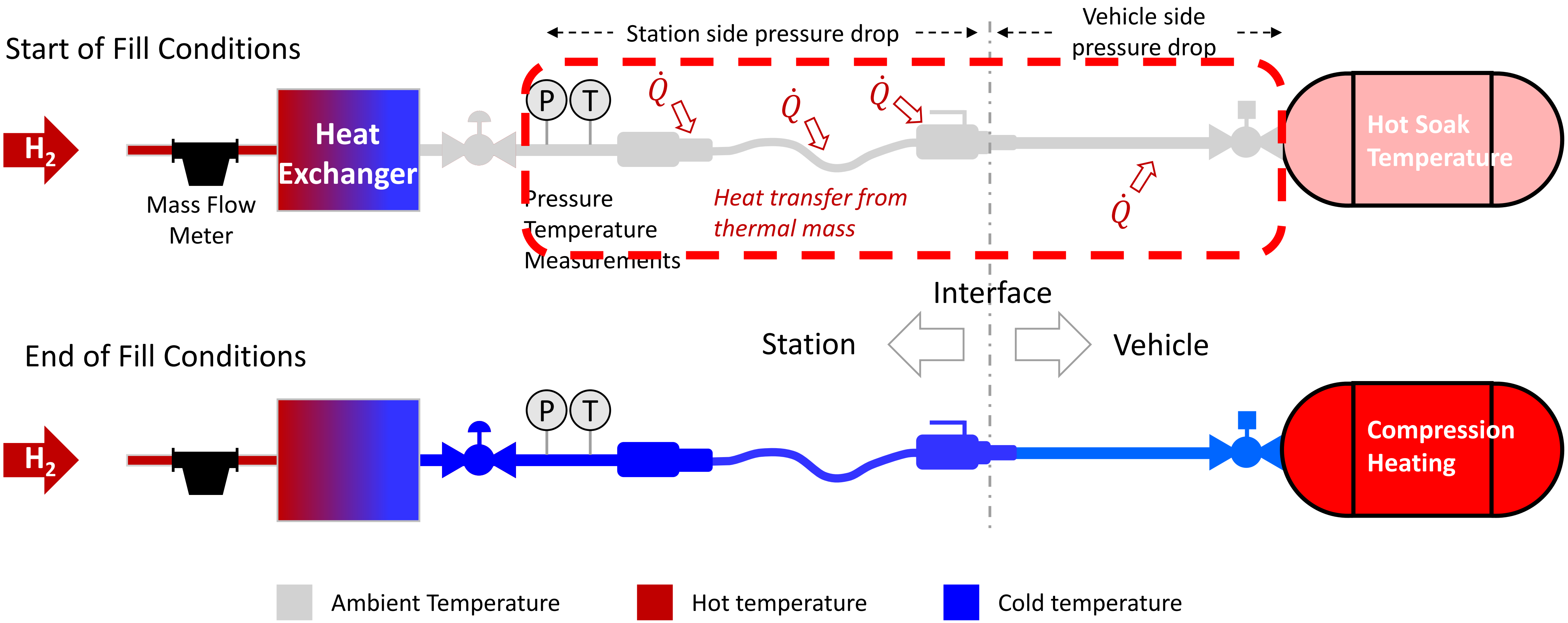
Ambient Temperature   Hot temperature   Cold temperature

Where does the margin come from?

SAE J2601 Worst Case Assumptions

Component assumptions

- Components with **highest thermal mass** and surface area
  - Components are **soaked at ambient temperature**

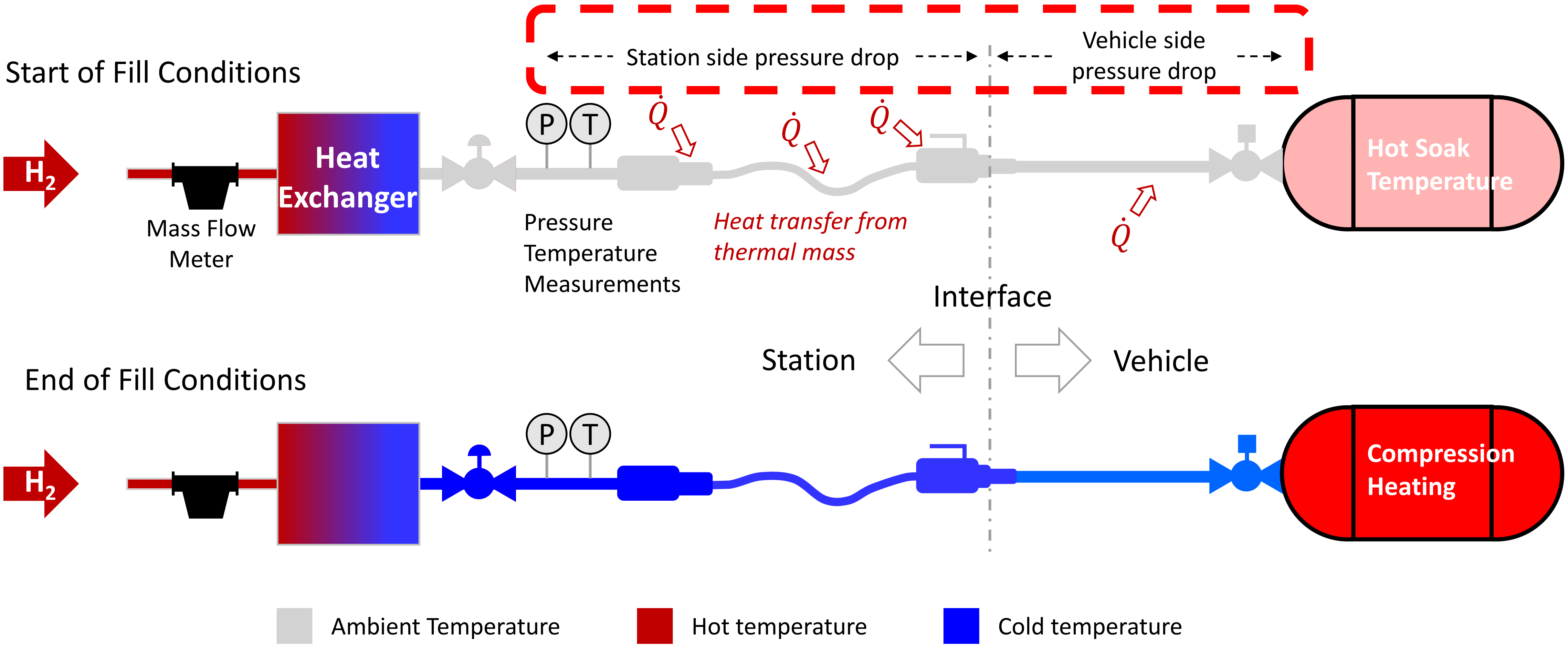


Where does the margin come from?

SAE J2601 Worst Case Assumptions

Pressure drop assumptions

- Highest possible pressure drop



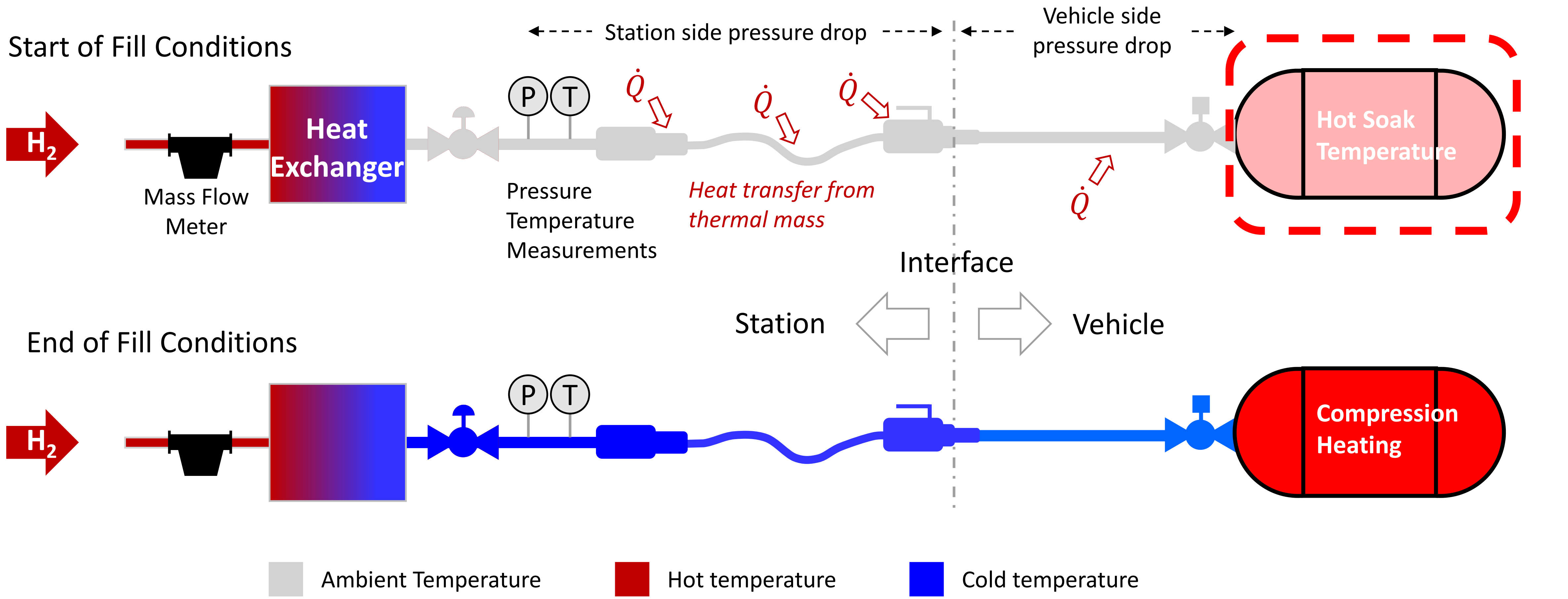
Where does the margin come from?

SAE J2601 Worst Case Assumptions

CHSS assumptions:

- 85 °C maximum gas temp
- Single tank (vs multiple)
- CHSS hot soaked
- Type IV construction w/low thermal conductivity
- Minimum initial pressure
- CHSS volume larger or smaller than actual*

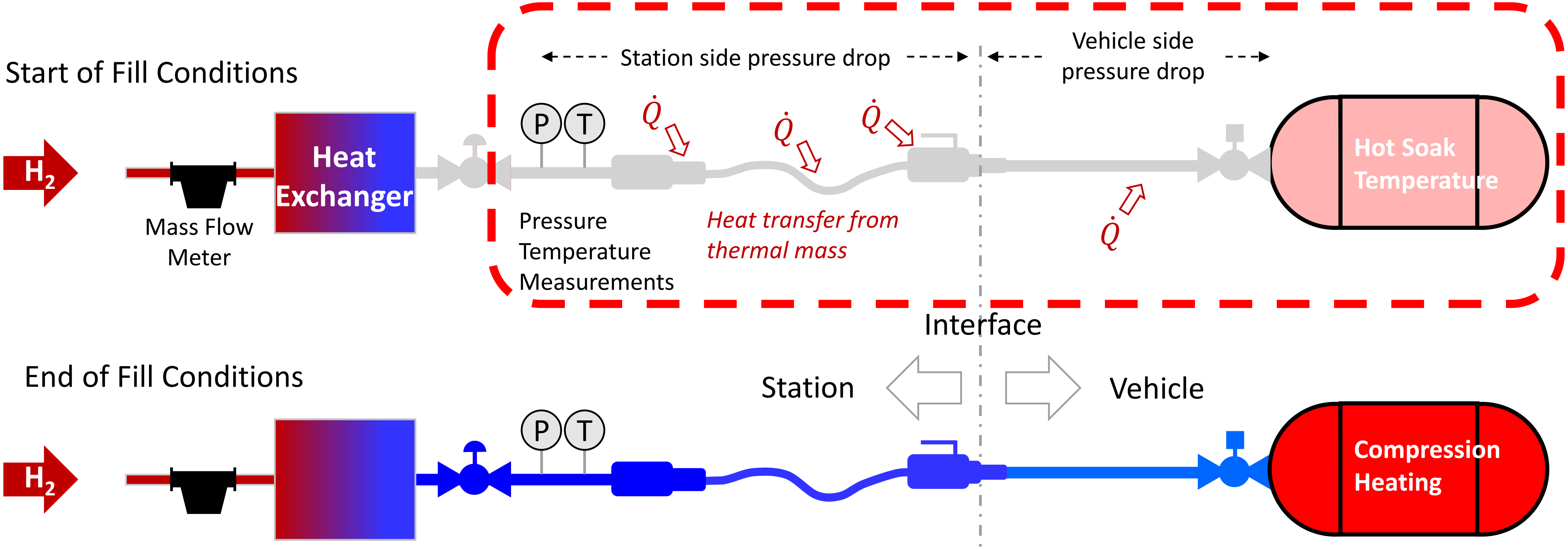
** Not applicable to MC Formula*



Where does the margin come from?

SAE J2601 Worst Case Assumptions

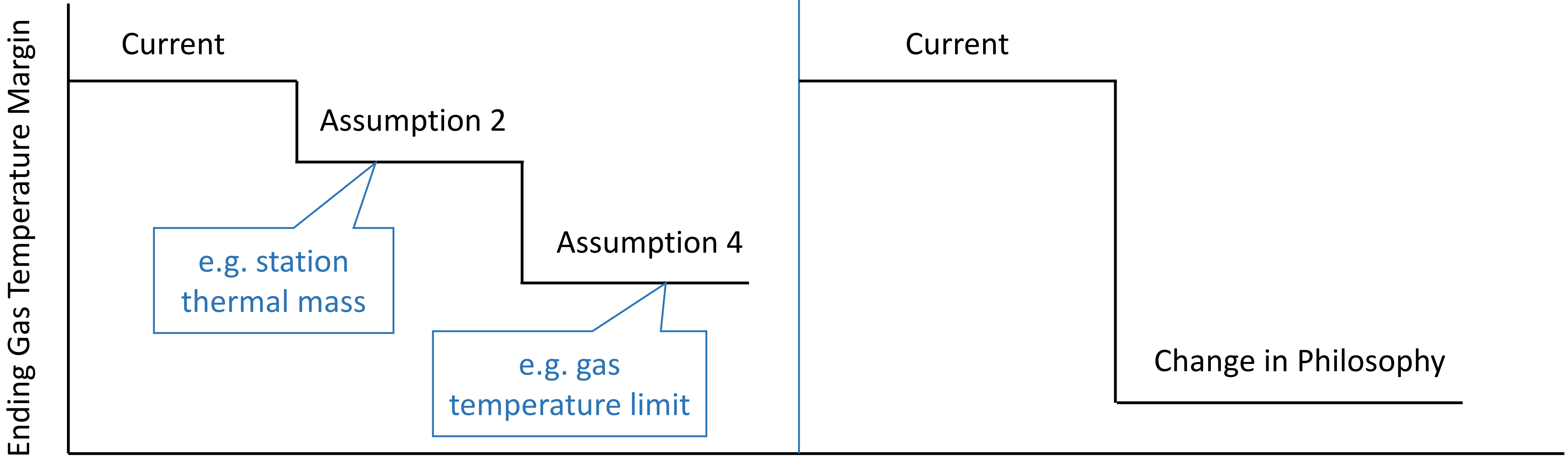
Real world fueling conditions are rarely at even one of these assumptions let alone all of them at the same time



- Margin comes from real world components and conditions being less conservative than the worst case assumptions in J2601

How can this margin be reduced?

Current SAE J2601 Philosophy (station responsible)	Revised philosophy (vehicle & station share responsibility)
➢ Improve the protocol by eliminating or reducing the embedded worst-case assumptions • Incremental improvements • Difficult to fully eliminate the margin	➢ Utilize new approaches which allow vehicle specific information to be communicated to the station and incorporated into the fueling protocol • Although benefits are high there are some trade-offs that need to be considered

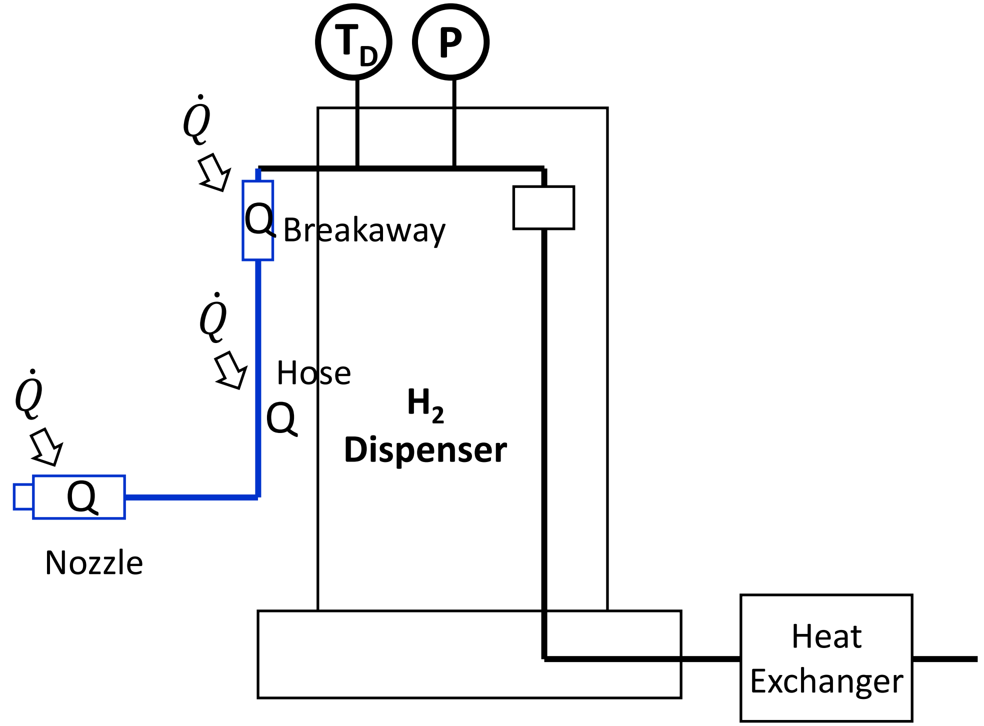


- Margin can be reduced incrementally with current philosophy or nearly eliminated with change in philosophy

J2601 Philosophy Margin Reduction – Station Components

Options:

1. Utilize the actual thermophysical properties of station components in the protocol development (instead of assuming the worst-case) *



* This approach is currently being researched under a NEDO funded project in Japan – see reference below:

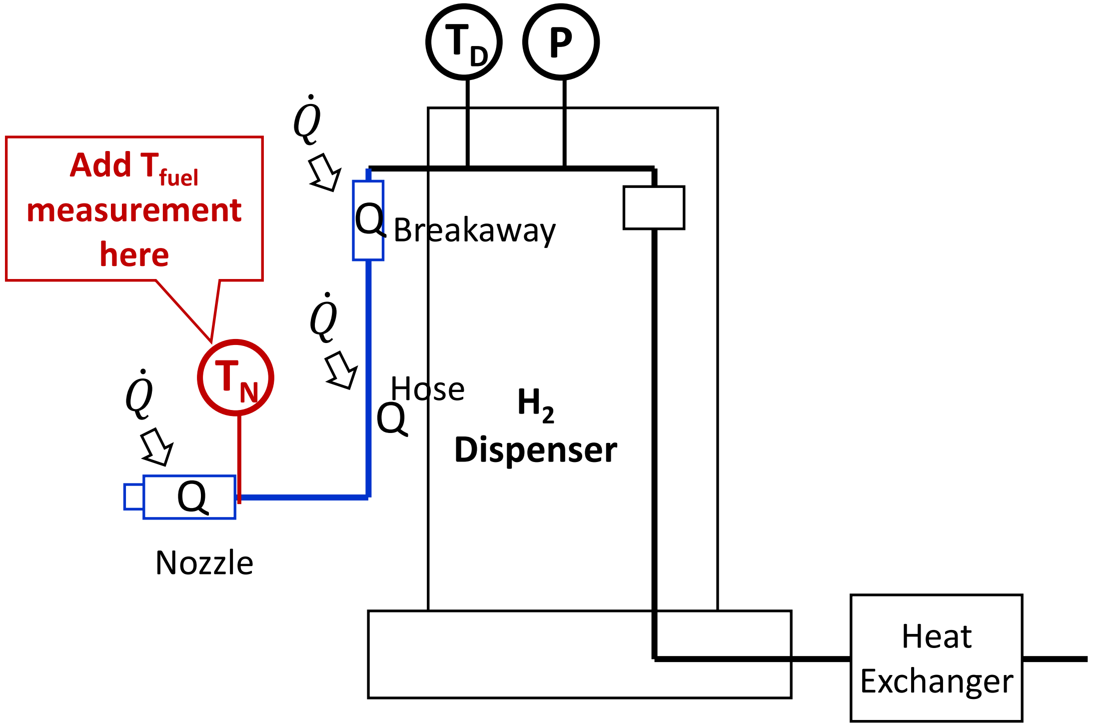
T. Kuroki, M. Peters, K. Nagasawa, D. Leighton N. Sakoda, K. Handa, S. Mathison, "Development of Hydrogen Fueling Model through Collaboration between Kyushu University and NREL,", International hydrogen infrastructure workshop 2020

J2601 Philosophy Margin Reduction – Station Components

Options:

1. Utilize the actual thermophysical properties of station components in the protocol development (instead of assuming the worst-case) *

2. Measure the fuel delivery temperature at the nozzle instead of upstream of the breakaway **



**

- Japan Patent 6602829 B2, K. Handa, "Gas Filling Method"
- US Patent Application US 20200173607 A1, S. Mathison, "Method and system for tank refueling using dispenser and nozzle readings"

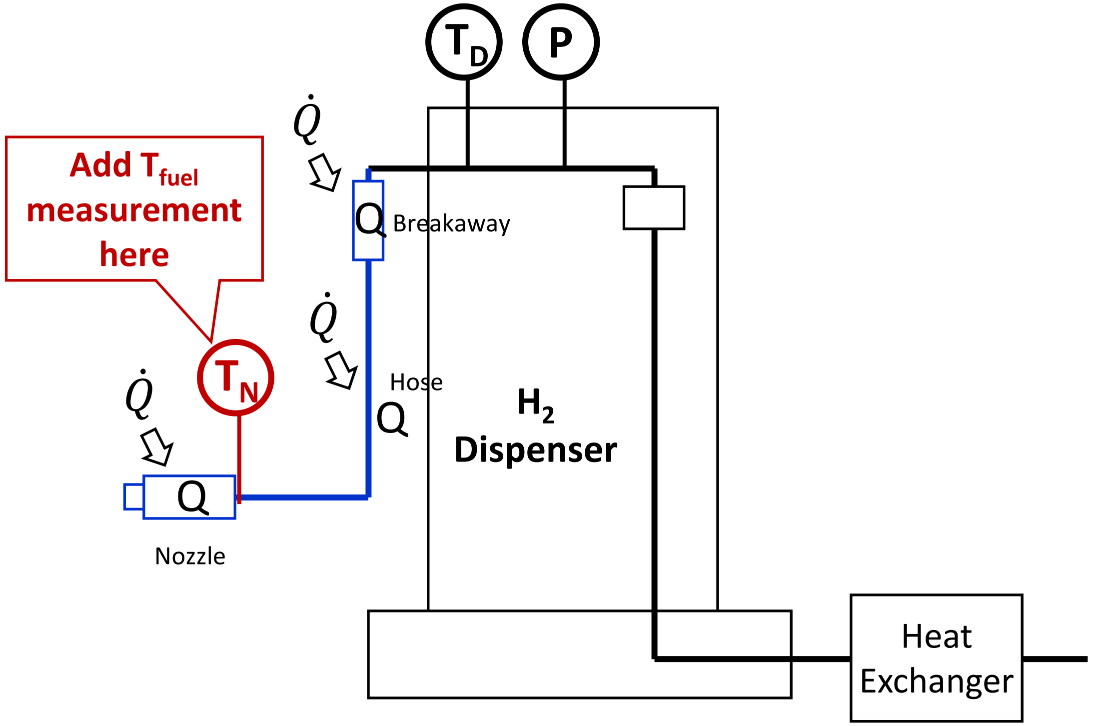
J2601 Philosophy Margin Reduction – Station Components

Options:

1. Utilize the actual thermophysical properties of station components in the protocol development (instead of assuming the worst-case) *
2. Measure the fuel delivery temperature at the nozzle instead of upstream of the breakaway

Option 2 solves two issues:

a. Only nozzle component properties considered
b. No assumption about component soak temperature



Because most stations use components with lower thermal mass and most fills start with components already cooled from a previous fill, this approach can reduce the margin and improve fueling

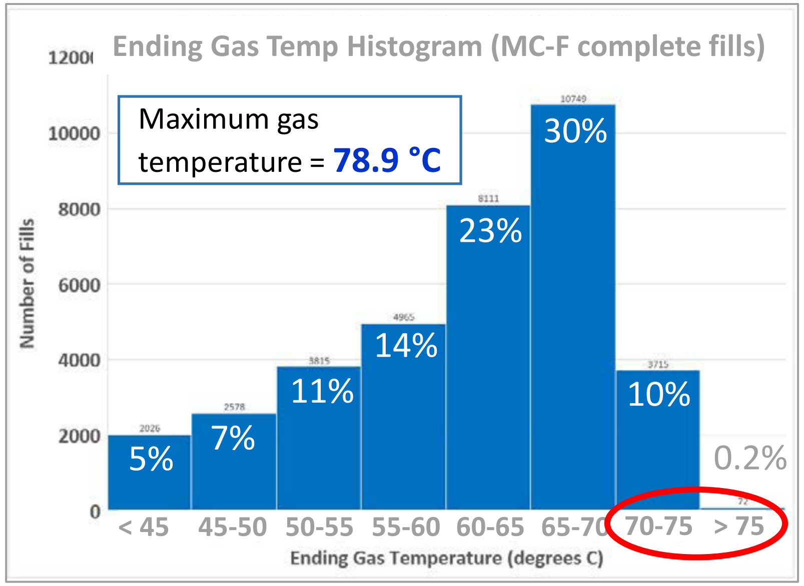
- **There are two options for reducing margin due to the effects of station component assumptions**
  - ✓ **Option 1 requires no changes to current component design**
  - ✓ **Option 2 would require adding a temperature measurement either in the nozzle or just upstream of the nozzle**

J2601 Philosophy Margin Reduction – Increase Gas Temp Limit

Current:

- ❑ SAE J2601 protocols are **designed not to exceed 85 °C** when all worst-case assumptions are present
- ❑ This **temperature limit is based on CHSS qualification testing** where 85 °C is the maximum temperature – i.e. UN GTR 13 and SAE J2579

Utilize 85 °C as the target for Protocol Design



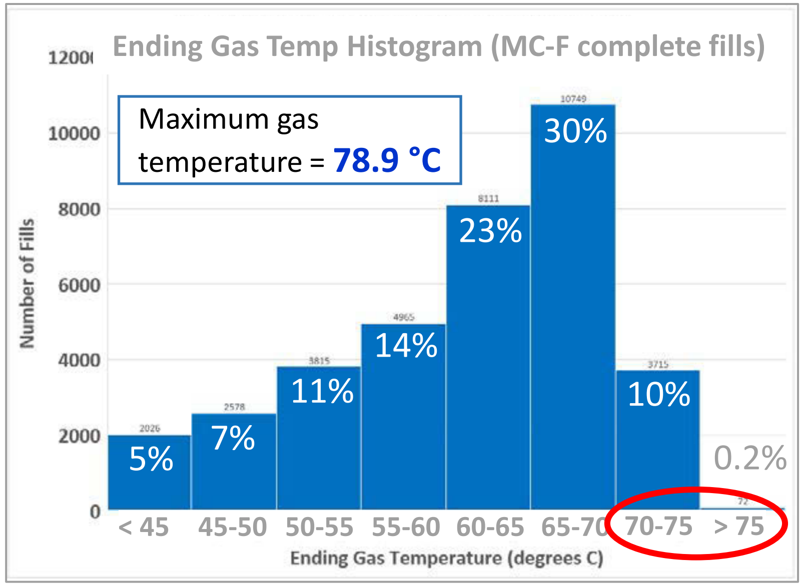
- SOC is good

J2601 Philosophy Margin Reduction – Increase Gas Temp Limit

Current:

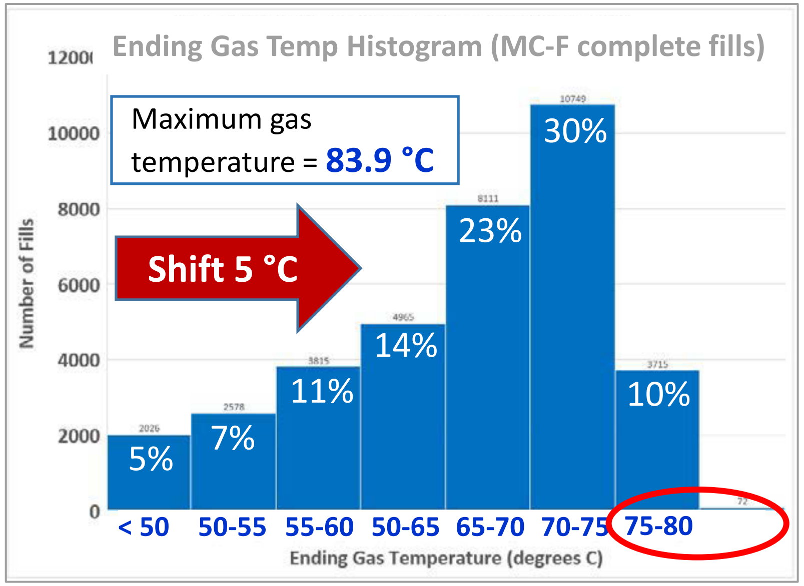
- SAE J2601 protocols are **designed not to exceed 85 °C** when all worst-case assumptions are present
- This **temperature limit is based on CHSS qualification testing** where 85 °C is the maximum temperature – i.e. UN GTR 13 and SAE J2579

Utilize 85 °C as the target for Protocol Design



- SOC is good

Utilize 90 °C as the target for Protocol Design



- SOC should still be acceptable

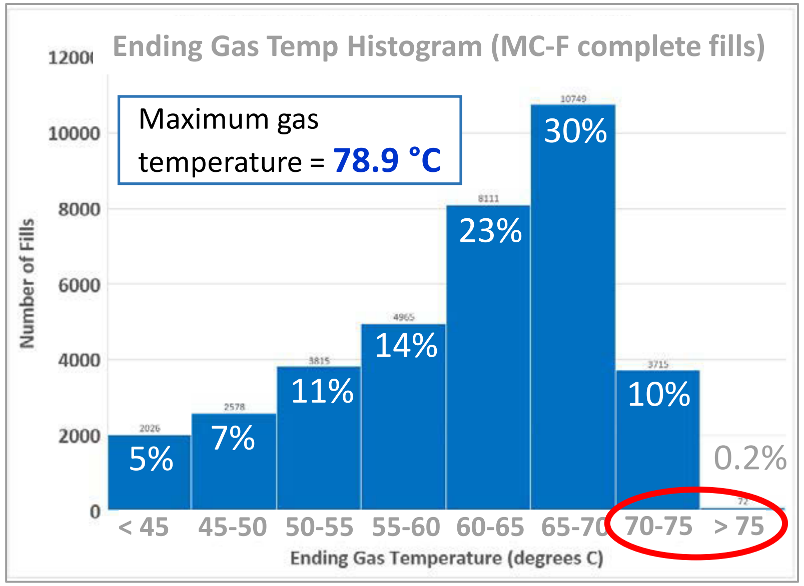
J2601 Philosophy Margin Reduction – Increase Gas Temp Limit

Current:

- ❑ SAE J2601 protocols are **designed not to exceed 85 °C** when all worst-case assumptions are present
- ❑ This **temperature limit is based on CHSS qualification testing** where 85 °C is the maximum temperature – i.e. UN GTR 13 and SAE J2579

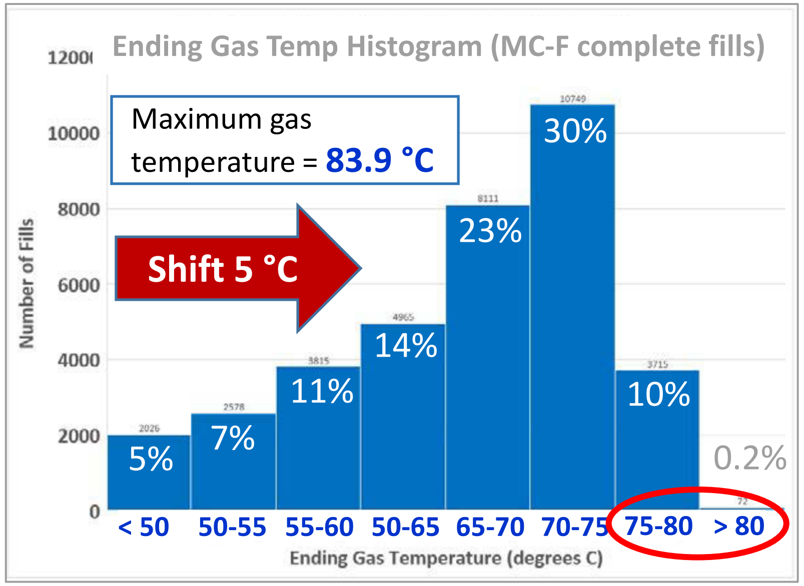
* Similar concept proposed by FCH-JU HyTransfer Project

Utilize 85 °C as the target for Protocol Design



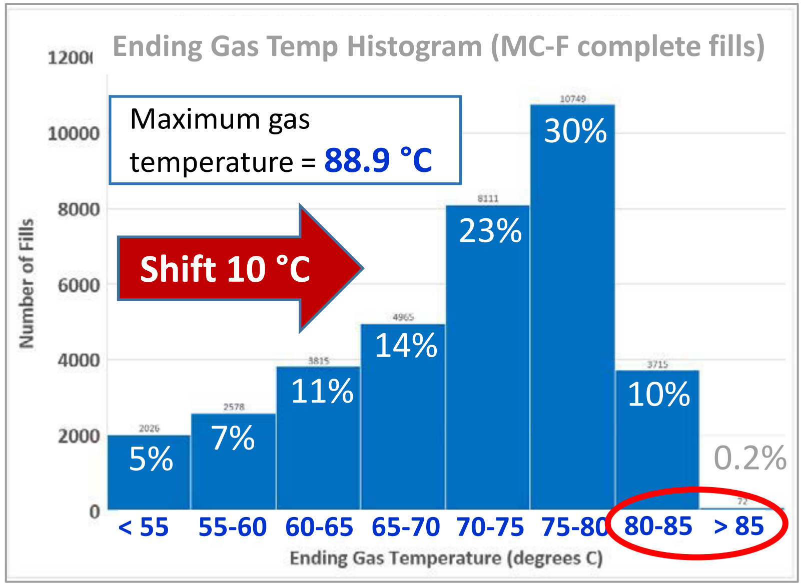
- SOC is good

Utilize 90 °C as the target for Protocol Design



- SOC should still be acceptable

Utilize 95 °C as the target for Protocol Design *



- SOC may be slightly lower on ~ 10% of fills

- Margin can be reduced by increasing the temperature limit used in the SAE J2601 protocol design
- This means that warmer pre-cooling temperatures could be used while keeping the fueling times the same as today

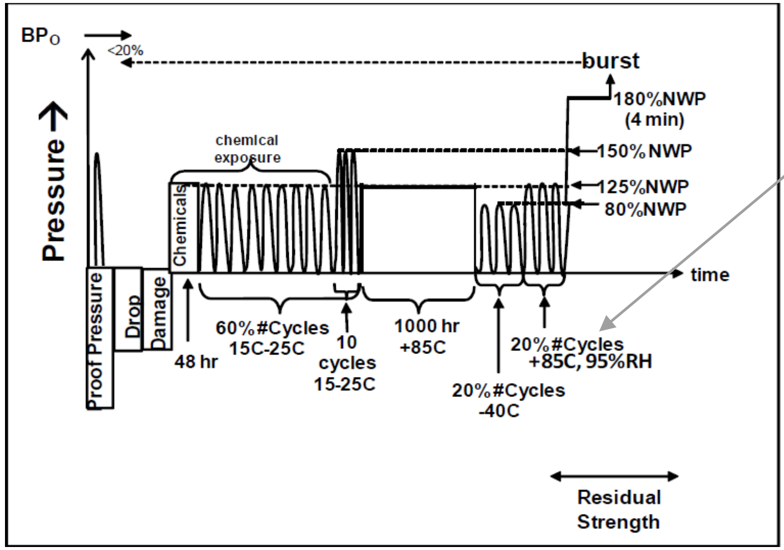
Implications of Increase in Gas Temperature Limit

Communications:

- ❑ To ensure backwards compatibility, vehicle may need to **communicate to station** the **CHSS gas temperature limit** → this may require a communication system with a higher functional safety than current IRDA (also changes philosophy)

CHSS Qualification Standards / Regulations:

- ❑ To incorporate this approach, it is likely that **changes to some GTR 13 requirements** would be needed.
- ❑ These **changes may include:**



<u>**5.1.2.6. Extreme temperature pressure cycling**</u>: The storage container is pressure cycled at …….. and at +85°C and 95 per cent relative humidity to 125 per cent NWP for 20 per cent number of Cycles…..

<u>**6.2.4.1. Gas pressure cycling**</u>: ……However, the pressure ramp rate should be decreased if the gas temperature in the container exceeds +85°C……

- Changes to the temperature specs in these clauses **may result in higher cost of the CHSS**
- A **cost-to-benefit analysis** may be needed to assess this approach to reducing margin

- **This approach to reducing margin would need deep discussion between key industry stakeholders and SDOs**

Change Philosophy – Vehicle CHSS Characteristics used for Control

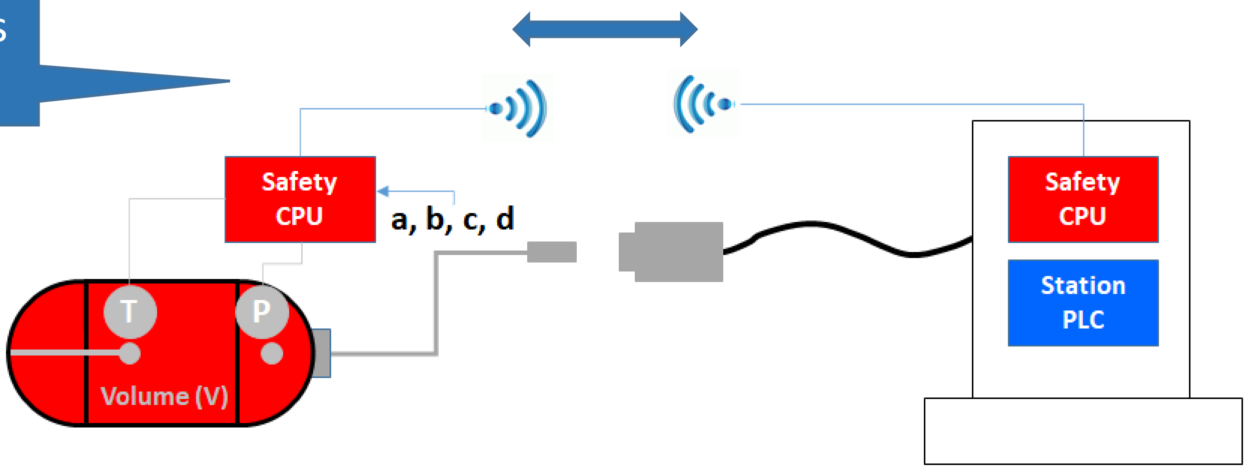
New Concept:

- ❑ The vehicle communicates **unique thermodynamic characteristics** of the CHSS + **Max Gas Temp**
  - Example: A unique set of coefficients used in the MC Formula protocol
- ❑ **The protocol calculates the pressure ramp rate based on these unique coefficients**

Current → **T, P, V** **+ T_{gas_max}** **+ (a, b, c, d)** ← **NEW**

- ❑ *Note that this approach may require an advanced communications protocol with higher functional safety than the current SAE J2799 IR-based protocol*

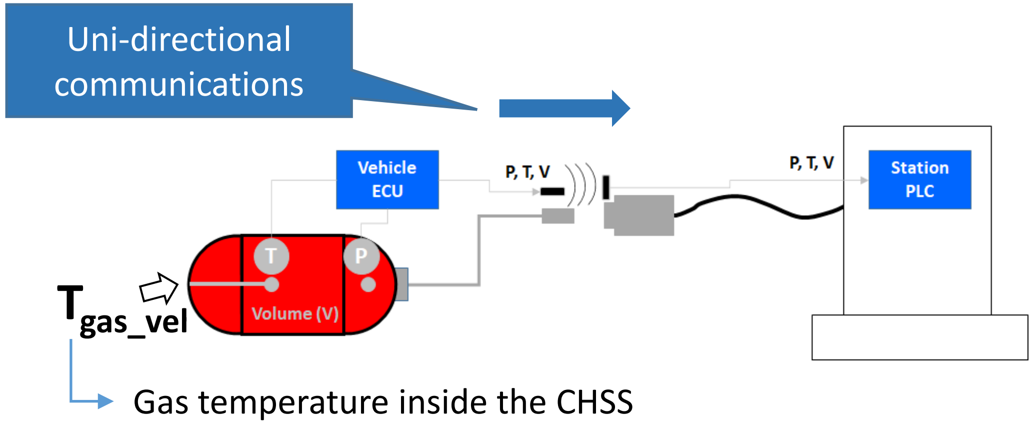
Bi-directional communications with high reliability



- ❑ Communicating unique CHSS thermodynamic coefficients to the station can reduce margin
- ❑ This approach may be especially useful for HD vehicles where it is difficult to make assumptions about worst-case designs

Change Philosophy → T_{gas_veh} used for Control

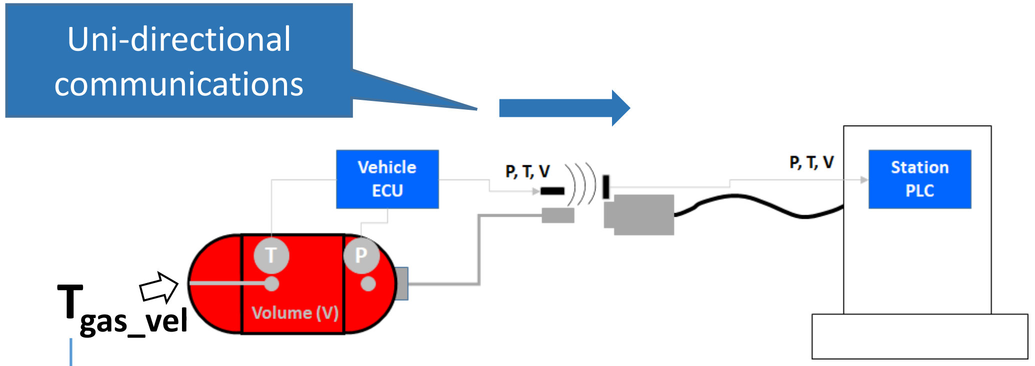
Current Approach:



- ❑ T_{gas_veh} **not used for fueling control**, only end of fill quality
- ❑ **T_{gas_veh} reliability is unknown to station**
- ❑ **Communications has limited value**
- ❑ **Communications cannot be used to reduce the margin**

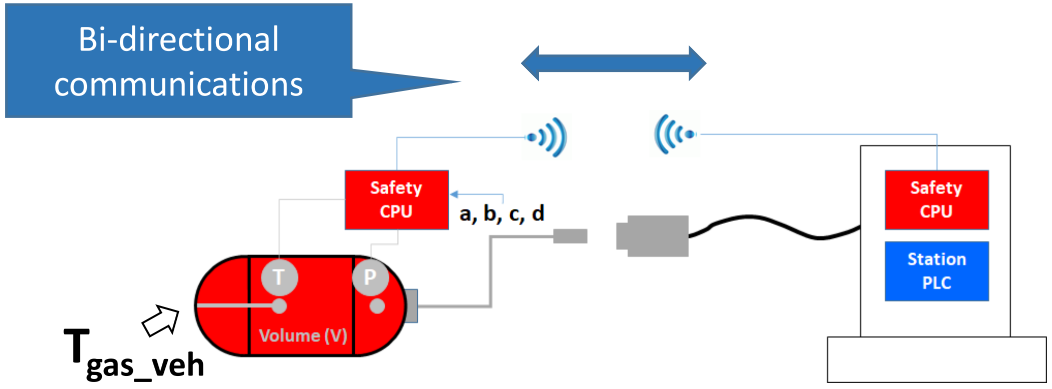
Change Philosophy → T_{gas_veh} used for Control

Current Approach:



- ❑ T_{gas_veh} **not used for fueling control**, only end of fill quality
- ❑ T_{gas_veh} **reliability is unknown to station**
- ❑ **Communications has limited value**
- ❑ **Communications cannot be used to reduce the margin**

Possible Future Approach:



- ❑ T_{gas_veh} – **high reliability measurement**
  - appropriate ASIL rank determined by OEM

- ❑ T_{gas_veh} **is used for fueling control**
- ❑ T_{gas_veh} **reliability needs to be sufficient** (fully trustworthy)
  - This includes **high system level functional safety**
  - **Temperature measurement AND *communications***
- ❑ **Communications adds value** – can utilize **feedback control**
- ❑ **Margin can be nearly fully reduced**, resulting in **faster fueling or warmer pre-cooling**
- ❑ The **downside** of this approach is:
  - **added cost to the vehicle (due to functional safety)**
  - **some liability is shifted from the station** to the vehicle

- Margin can be nearly fully reduced by utilizing T_{gas} in the fueling control with a fundamental change in philosophy

T_{gas_veh} used for Control → Two Options

Option A (pure feedback control)

T_{gas_veh}, $T_{gas\_veh\_Max}$, P, V, $GTR13_{compliance}$, etc

- Station uses **only T_{gas_veh} for feedback control**
- **Positives:**
  - **Very simple, non-prescriptive fueling protocol**
- **Negatives:**
  - **If T_{gas_veh} has a fault, gas temp could greatly exceed 85 °C**
  - **High reliability required for vehicle or CHSS robust to faults**
  - **Vehicle takes on significant liability**

T_{gas_veh} used for Control → Two Options

Option A (pure feedback control)

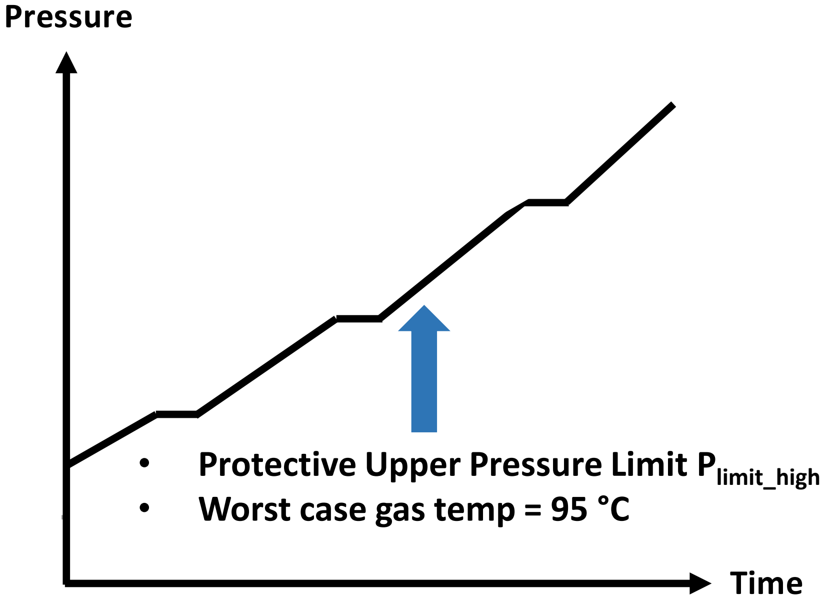
T_{gas_veh}, $T_{gas\_veh\_Max}$, P, V, $GTR13_{compliance}$, etc

- Station uses **only T_{gas_veh} for feedback control**
- **Positives:**
  - **Very simple, non-prescriptive fueling protocol**
- **Negatives:**
  - **If T_{gas_veh} has a fault, gas temp could greatly exceed 85 °C**
  - **High reliability required for vehicle or CHSS robust to faults**
  - **Vehicle takes on significant liability**

Option B (Hybrid - feedback control w/ back-stop)

a, b, c, d, T_{gas_veh}, $T_{gas\_veh\_Max}$, P, V, $GTR13_{compliance}$, etc

MC Formula coefficients based on maximum temperature rating of CHSS (e.g. 95 °C)



T_{gas_veh} used for Control → Two Options

Option A (pure feedback control)

T_{gas_veh}, $T_{gas\_veh\_Max}$, P, V, $GTR13_{compliance}$, etc

- Station uses **only T_{gas_veh} for feedback control**
- **Positives:**
  - **Very simple, non-prescriptive fueling protocol**
- **Negatives:**
  - **If T_{gas_veh} has a fault, gas temp could greatly exceed 85 °C**
  - **High reliability required for vehicle or CHSS robust to faults**
  - **Vehicle takes on significant liability**

Option B (Hybrid - feedback control w/ back-stop)

a, b, c, d, T_{gas_veh}, $T_{gas\_veh\_Max}$, P, V, $GTR13_{compliance}$, etc

MC Formula coefficients based on maximum temperature rating of CHSS (e.g. 95 °C)

- Station **uses T_{gas_veh} for feedback control**, but **with protective back-stop in case T_{gas_veh} is wrong** (has a fault condition)
- **Positives:**
  - **Benefits of pure feedback control**, but if there is a fault, the **max gas temperature is limited** due to **back-stop** function
  - Much **lower functional safety requirements** on vehicle
  - **Lower liability** for vehicle
- **Negatives:**
  - Must **qualify CHSS to higher temperature rating > 85 C** which could result in **higher cost**

Two Options: A (direct feedback control) requires very high reliability of gas temperature measurement and communication
B (hybrid approach) where vehicle provides parameters to station for a “backstop” in case T_{gas_veh} is wrong

Benefits of Margin Reduction

Warmer Pre-cooling Temperatures

- ❑ Computer **fueling simulations show** that for **every 1 °C increase in CHSS gas temperature**, the **pre-cooling temperature can be increased by approximately 1.5 °C**
- ❑ With the various approaches discussed, CHSS gas temperature can be increased by up to 10 °C with the same fueling times
- ❑ Therefore**, for Light Duty fueling, pre-cooling temperatures** can be **increased by up to + 15 °C (from current T40 to T20)**
- ❑ **For Heavy Duty fueling, it may be possible to increase pre-cooling temperatures to T10 (- 10 °C) due to multi-tank CHSS**

Benefits

- ❑ **Capital and operating cost reductions, higher component reliability, improved station up-time**
  - A study by Dr. Elgowainy * shows the total **pre-cooling systems costs** (capital + operating) can be **25% lower at T20 vs T40**
  - A **dispenser reliability testing program** ** conducted by Peters et al **at NREL** demonstrated that the **reliability of components** exposed to cold gas (valves, breakaways, nozzles) are **significantly higher at T20 temperatures than at T40**
    - Over the testing period: **20 component failures at T40** vs only **8 component failures at T20**

* ***Analysis of Incremental Fueling Pressure Cost***, A. Elgowainy, K. Reddi, 2015 DOE AMR Presentation

** ***Dispenser Reliability Project Report***, M. Peters, N. Menon, M. Ruple, A. Winkler, K. Hartmann, E. Hecht, 2020 DOE AMR Presentation

- Pre-cooling temperatures can be increased by up to 15 °C (to T20) while keeping same fueling performance as today
- Alternatively, fueling times can be significantly reduced to accommodate stations with very high throughput requirements

Summary and Future Work

Summary

- ❑ Using the MC Formula fueling protocol, today's **fueling performance looks to be acceptable**
- ❑ However, there is about **10 °C of temperature margin embedded**, causing pre-cooling to be colder than necessary
- ❑ With **current J2601 philosophy, incremental reductions in margin** can be made such as those shown
- ❑ Using a **revised philosophy,** or by using a **higher ending gas temp limit**, **most of this margin can be eliminated**
- ❑ **New fueling protocol approaches are especially appealing for high flow HD fueling due to the nascent market and higher fuel cost sensitivity**

Potential Future Work

- ❑ **Rigorously assess** these fueling methods, **focusing on high flow HD fueling** due to **nascent market** and **high fuel cost sensitivity**
- ❑ Utilize a **techno-economic** based **Total Cost of Ownership (TCO) analysis**
  - Some approaches will cause costs on vehicle to increase but costs on station to decrease – need to understand the balance
- ❑ T40 → T20: **Holistic assessment of costs**, including **implications on compression and storage** due to higher ending gas pressures
  - Especially with higher gas temp limits, it may be possible to go to **T10 or even T0 pre-cooling** – again assess with TCO
- ❑ **NREL has the capabilities and tools to assess these approaches**
  - **Modeling and testing** of new fueling methods, **component** testing, **reliability** testing, **techno-economic assessments**, etc.

Acknowledgement and Contact

Acknowledgement:

The development of the MC Formula fueling protocol, and the research into many of the advanced concepts explored in this presentation, were supported by Honda R&D Americas LLC and the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office, within the Office of Energy Efficiency and Renewable Energy.

I would also like to acknowledge Wenger Engineering for supporting the R&D of the MC Formula protocol via computer based fueling simulations.

And finally, I would like to acknowledge the members of the SAE Fuel Cell Standards Committee Interface Task Force, which I have had the privilege to chair, for volunteering their time and expertise towards the development of the SAE J2601 standard.

Contact:

You can reach me at: steven.mathison@nrel.gov

Notice: