Overview of the SAE J2601 MC Formula H2 Fueling Protocol

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Outline

- Background
- Overview of the MC Formula Protocol
- MC Formula Validation Calculator
- MC Formula Protocol Validation (CSA HGV 4.3)
- Usage of MC Formula Protocol in the United States
- Conclusion

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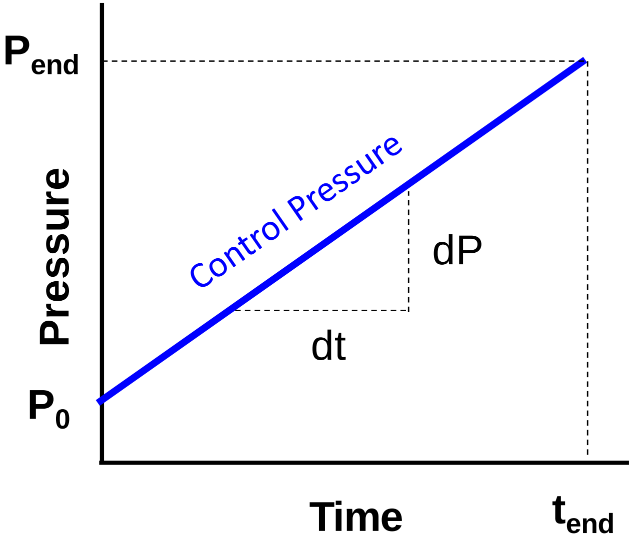
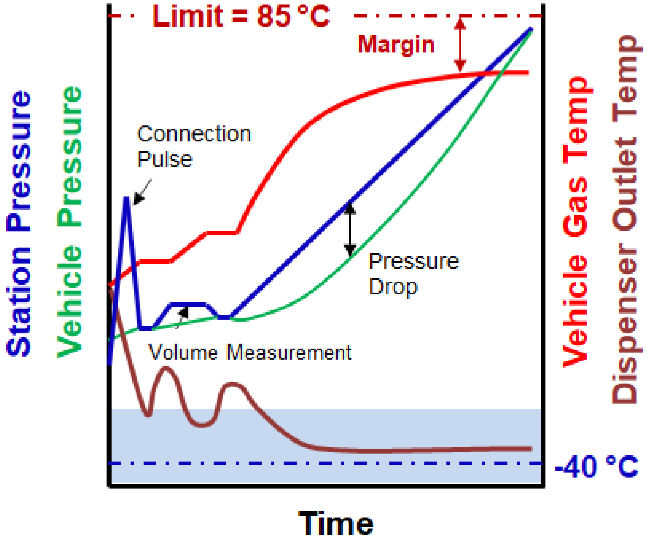
Fueling Protocol Overview

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

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

Korea

All public stations required to utilize 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

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020

Intense development period
(simulations, bench testing, field testing)

TIR J2601 (2010)
Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

Standardize Table-based protocol

J2601 (2014)
Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

J2601-3 (2013)
Fueling Protocol for Gaseous Hydrogen Powered Industrial Trucks

J2601-2 (2014)
Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles

Standardize MC Formula-based protocol

J2601 (2016)
Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

Edits for clarification & extends the protocols to facilitate fueling of larger CHSS systems above 250 liters (10 kg H70)

J2601 (2020)
Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

TIR J2601-4 (2020)
Ambient Temperature Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

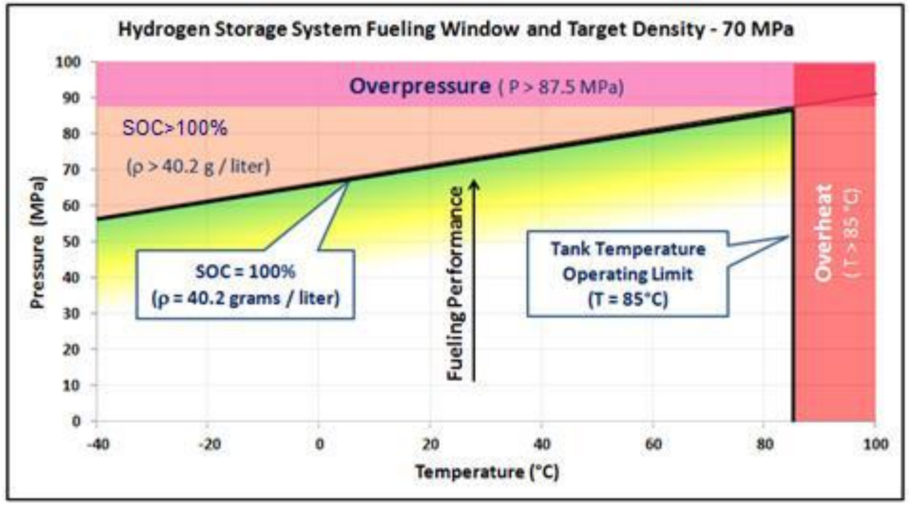
- There are a family of SAE J2601 fueling protocol standards to address the needs of light duty, H35 heavy duty, and forklifts

SAE J2601 Philosophy

Philosophy for SAE J2601 Fueling Protocols:

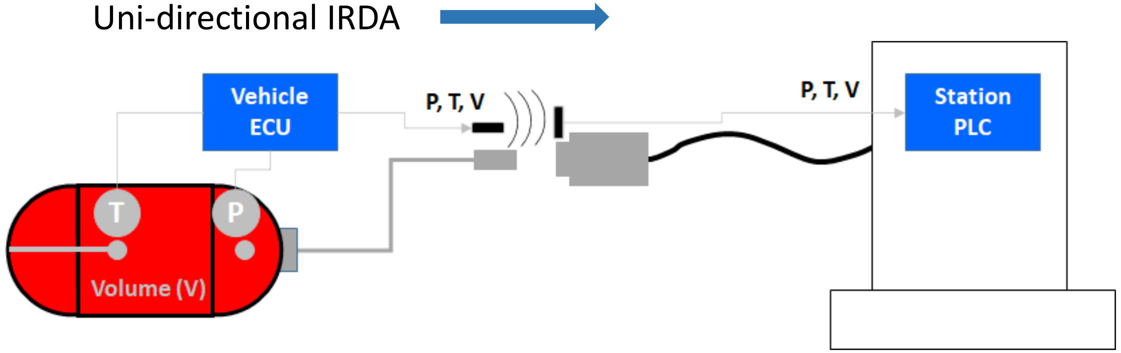
- ➢ H_2 Station is fully responsible for safe fueling of the vehicle
- ➢ No safety critical information from vehicle is used *
- ➢ Worst case boundary conditions are assumed

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 Options and Their Structures

Table-base Protocol

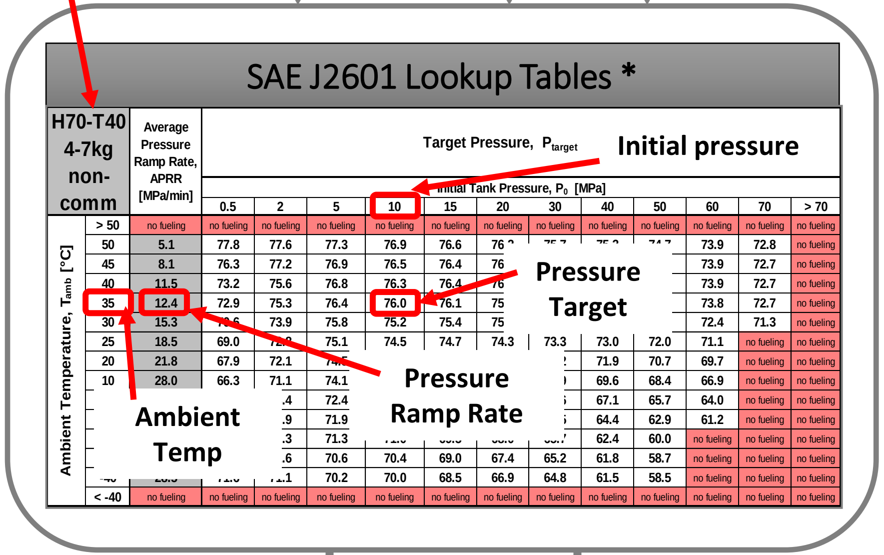
Inputs

Vehicle Parameters: Initial Gas Pressure

Station Parameters: Ambient Temp. · Delivered Gas Temp.

Boundary

Fuel Temperature (T40 = -40 °C)



Outputs

Ending Pressure · Constant Pressure Ramp Rate

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

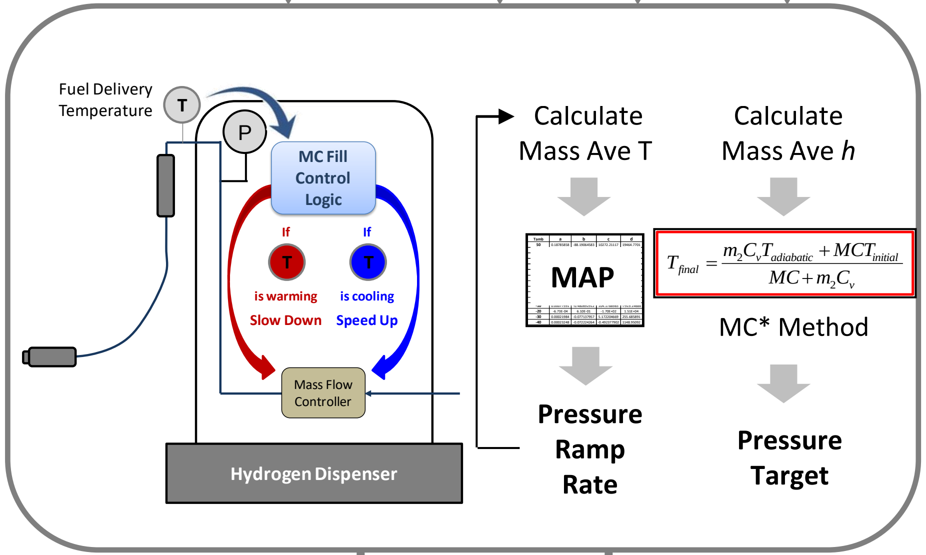
Refueling Control is *Static*

MC Formula Protocol

Inputs

Vehicle Parameters: Initial Gas Pressure

Station Parameters: Ambient Temp. · Delivered Gas Temp. · Delivered Gas Press.



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

"MC" denotes the heat capacity of the tank system

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

Outputs

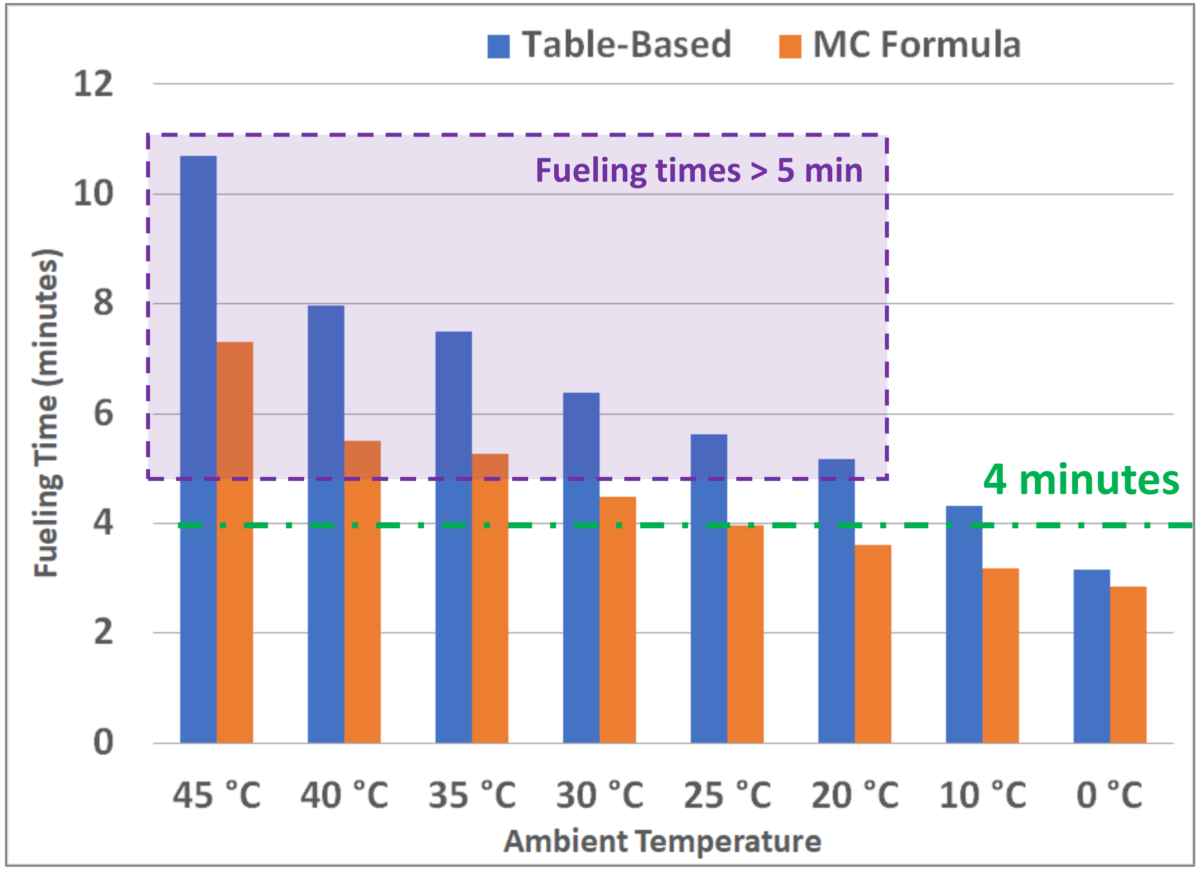
Ending Pressure · Variable Pressure Ramp Rate

Refueling Control is *Dynamic*

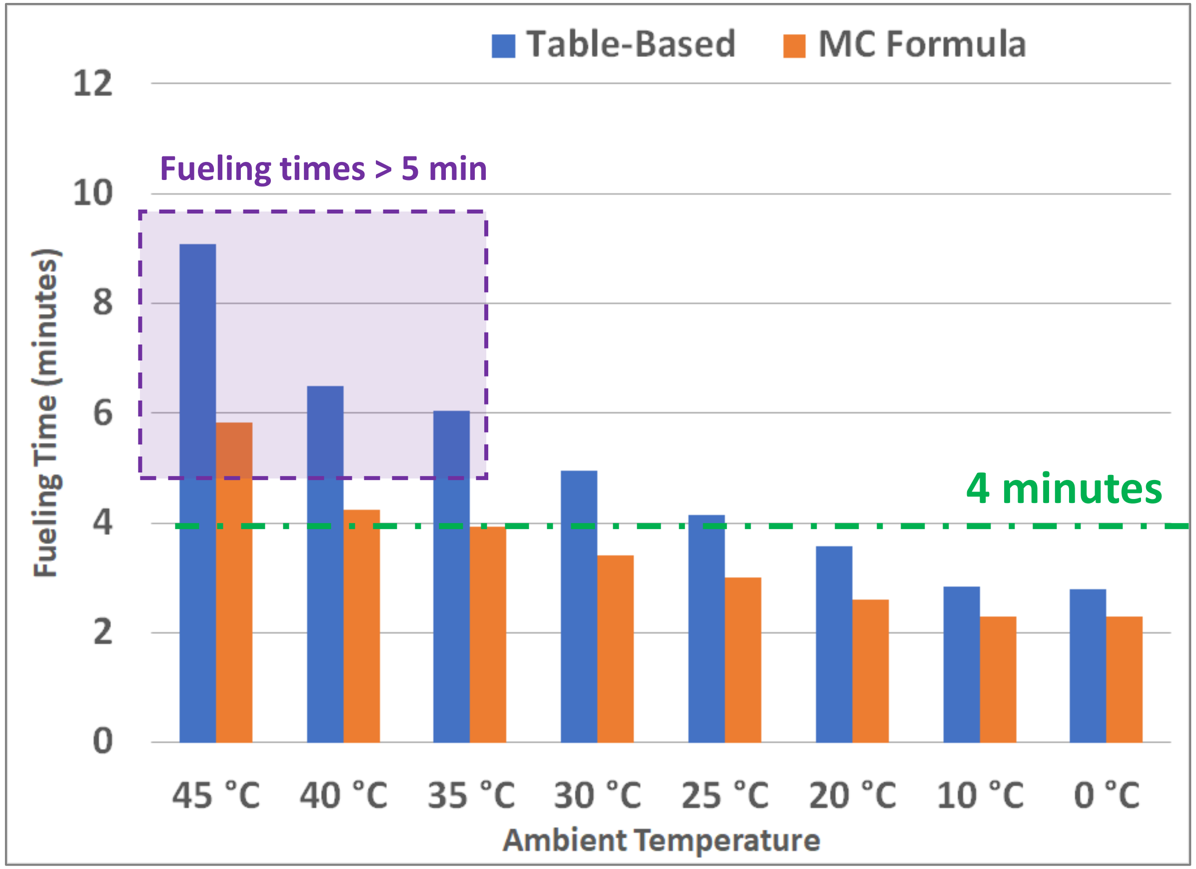
- There are two **standard fueling protocols** in SAE J2601 – Table-based and MC Formula
- Table-based protocol uses **static control** whereas MC Formula uses **feed-forward dynamic control**

Fueling Performance - Potential

Initial Pressure = 2 MPa (~ 4% SOC)



Initial Pressure = 10 MPa (~ 20% SOC)



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**

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- **Overview of the MC Formula Protocol**
- MC Formula Validation Calculator
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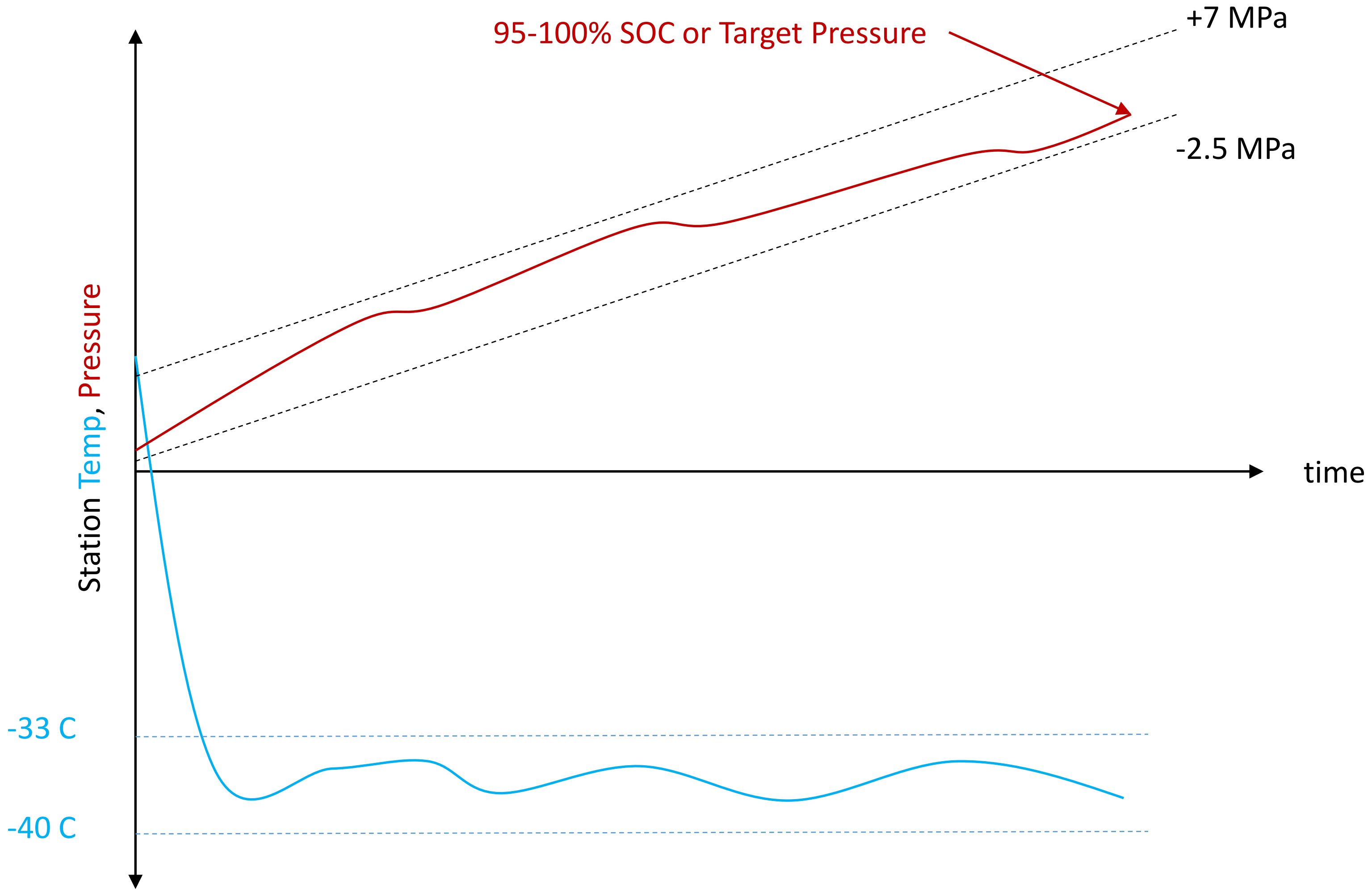
Overview – Generic Fueling Profile

Example shows typical T40 Fill

- Station (fuel) temperature between -33 to -40 C
- Pressure within target corridor (+7.0/-2.5 MPa)
- Fill stops at
  - 95-100% SOC (communications) or
  - Target Pressure



Overview – Table Based Fueling Protocol

- **Table based Fueling Protocol uses Average Pressure Ramp Rate (APRR) to control fueling speed**
- **Average Pressure Ramp Rate (APRR) based upon**
  - Station Pressure Class (H35 / H70)
  - Fuel Delivery Temp Category
  - CHSS Capacity (vehicle tank size) Category
  - Ambient Temperature

H70-T40 Capacity Category B Non-Comm		APRR [MPa/min]	Target Pressure, P_{target} [MPa]											
			Initial Tank Pressure, P_0 [MPa]											
			0,5	2	5	10	15	20	30	40	50	60	70	>70
Ambient Temperature, T_{amb} [°C]	>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,[illegible]	77,8	77,6	77,3	76,9	76,6	76,2	75,7	75,3	74,7	73,9	72,8	no fueling
	45	8,[illegible]	76,3	77,2	76,9	76,5	76,4	76,2	75,6	75,3	74,7	73,9	72,7	no fueling
	40	11,5	73,2	75,6	76,8	76,3	76,4	76,2	75,6	75,3	74,6	73,9	72,7	no fueling
	35	12,4	72,9	75,3	76,4	76,0	76,1	75,9	75,3	75,1	74,5	73,8	72,7	no fueling
	30	15,3	70,6	73,9	75,8	75,2	75,4	75,1	74,3	74,1	73,3	72,4	71,3	no fueling
	25	18,5	69,0	72,8	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	74,5	73,7	74,0	73,4	72,2	71,9	70,7	69,7	no fueling	no fueling
	10	28,0	66,3	71,1	74,1	73,2	72,4	71,6	70,9	69,6	68,4	66,9	no fueling	no fueling
	0	28,5	74,0	73,4	72,4	70,6	70,7	69,6	68,6	67,1	65,7	64,0	no fueling	no fueling
	-10	28,5	73,4	72,9	71,9	70,0	70,0	68,4	66,5	64,4	62,9	61,2	no fueling	no fueling
	-20	28,5	72,9	72,3	71,3	71,0	69,5	68,0	65,7	62,4	60,0	no fueling	no fueling	no fueling
	-30	28,5	72,1	71,6	70,6	70,4	69,0	67,4	65,2	61,8	58,7	no fueling	no fueling	no fueling
	-40	28,5	71,6	71,1	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

Overview – Table Based Fueling Protocol: APRR

- **For Table Based Fueling Protocol, target APRR**
  - **Does not directly depend on Fuel Delivery Temperature (only the "T" category)**
  - **Constant**
- **Calculated at start of fill**

H70-T40 Capacity Category B Non-Comm	APRR [MPa/min]	Target Pressure, P_{target} [MPa]											
		Initial Tank Pressure, P_0 [MPa]											
Ambient Temperature, T_{amb} [°C]		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	76,2	75,7	75,3	74,7	73,9	72,8	no fueling
45	8,1	76,3	77,2	76,9	76,5	76,4	76,2	75,6	75,3	74,7	73,9	72,7	no fueling
40	11,5	73,2	75,6	76,8	76,3	76,4	76,2	75,6	75,3	74,6	73,9	72,7	no fueling
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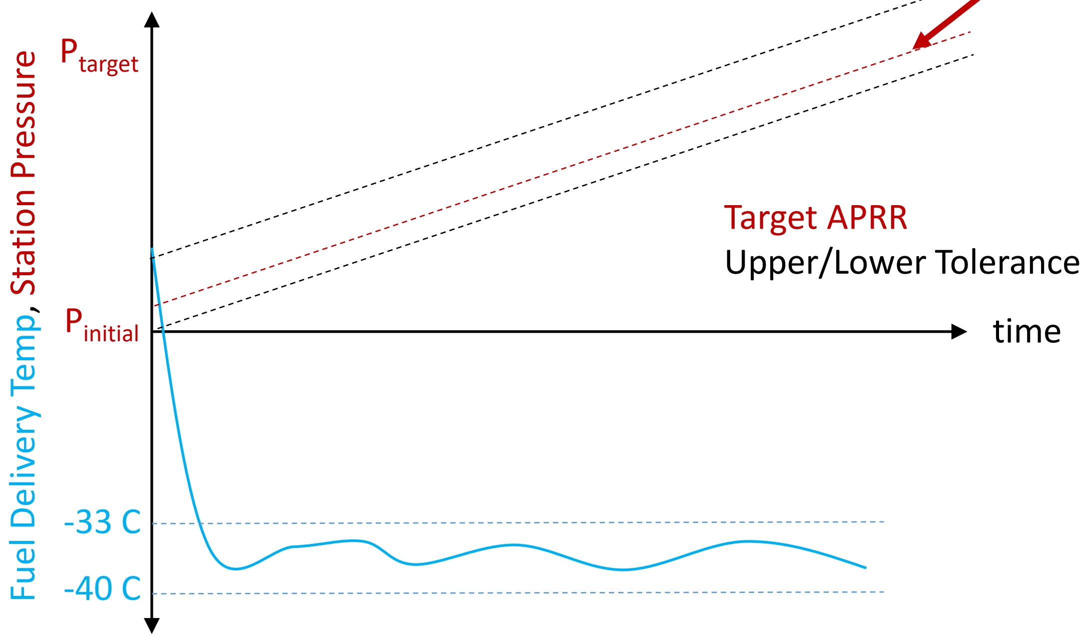
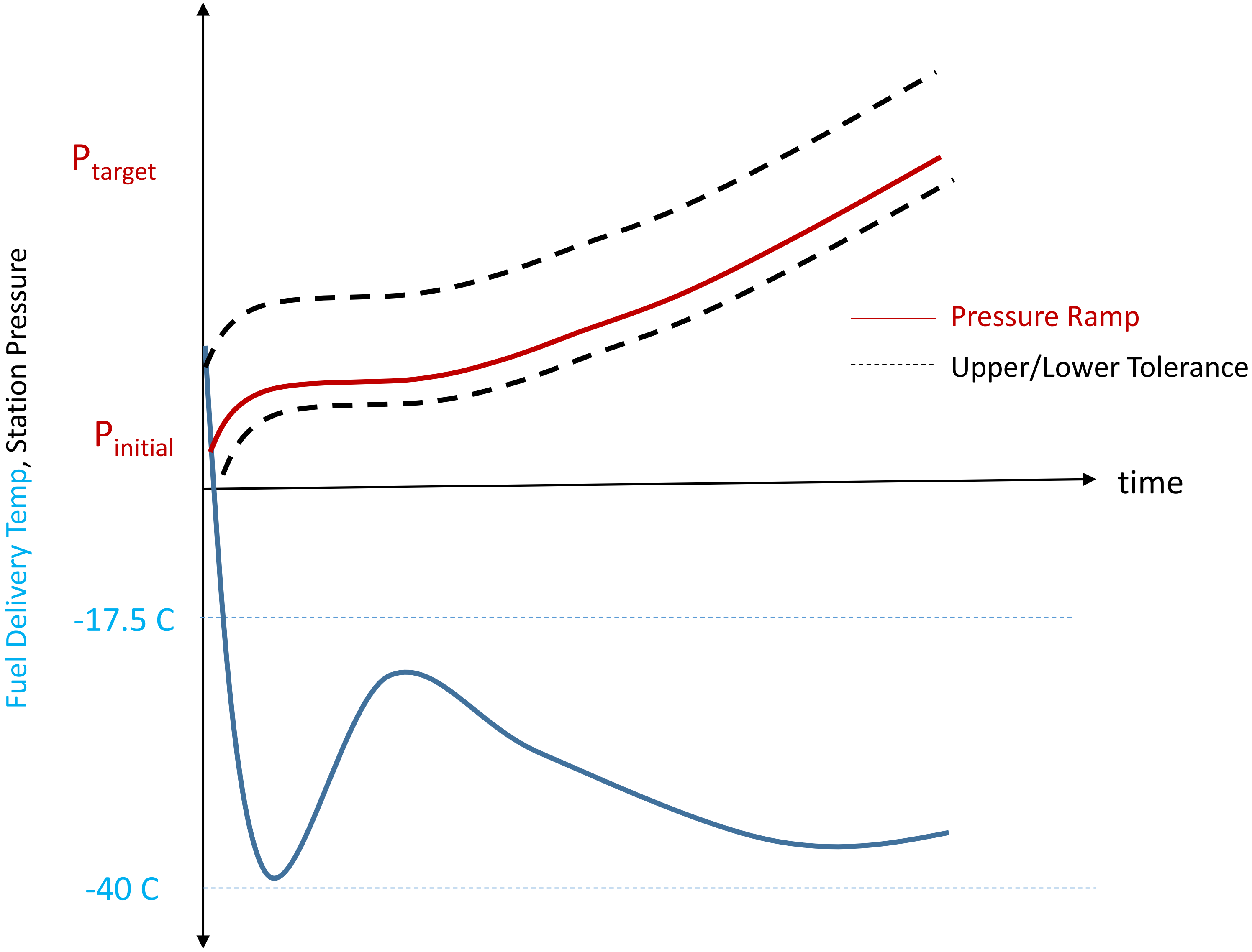
30	15,3	70,6	73,9	75,8	75,2	75,4	75,1	74,3	74,1	73,3	72,4	71,3	no fueling
25	18,5	69,0	72,8	75,1	74,5	74,7	74,3	73,3	73,0	72,0	71,1	no fueling	no fueling
20	21,8	67,9	72,1	74,5	73,7	74,0	73,4	72,2	71,9	70,7	69,7	no fueling	no fueling
10	28,0	66,3	71,1	74,1	73,2	72,4	71,6	70,9	69,6	68,4	66,9	no fueling	no fueling
0	28,5	74,0	73,4	72,4	70,6	70,7	69,6	68,6	67,1	65,7	64,0	no fueling	no fueling
-10	28,5	73,4	72,9	71,9	70,0	70,0	68,4	66,5	64,4	62,9	61,2	no fueling	no fueling
-20	28,5	72,9	72,3	71,3	71,0	69,5	68,0	65,7	62,4	60,0	no fueling	no fueling	no fueling
-30	28,5	72,1	71,6	70,6	70,4	69,0	67,4	65,2	61,8	58,7	no fueling	no fueling	no fueling
-40	28,5	71,6	71,1	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



Overview – MC Formula: Pressure Ramp Rate

- **For MC Fueling Protocol, Pressure Ramp Rate (PRR) is**
  - Based directly upon on Fuel Delivery Temperature
  - Varies during the fill
  - Calculated every second of fill



Overview – MC-F: Fuel Delivery Temperature Categories

- Same as Table based, except for T40 → T40 upper limit temperature increases with decreasing ambient temperature
- Based upon the end of fill value of the Mass Average Temperature (MAT) started at t = 30 seconds (MAT_{30})
- MAT_{30} may exceed limits during the fill – the "T" rating is based on MAT_{30} at the end of the fill

Fuel Delivery Temperature Category		$-40\ °C \le MAT_{30} \le T40limit$	$-33\ °C < MAT_{30} \le -26\ °C$	$-26\ °C < MAT_{30} \le -17.5\ °C$
Station Designator	35 MPa NWP	H35-T40	H35-T30	H35-T20
	70 MPa NWP	H70-T40	H70-T30	H70-T20

where

T_{amb} (°C)	$T40limit$ (°C)
≥20	-33
15	-32.5
10	-32
0	-29
-10	-28
-20	-27
-30	-26.5
-40	-26

For the T40 category, the fuel delivery temperature can be warmer at cold ambient temperatures

Overview – MC Formula: CHSS Categories

- MC Formula is the same as Table-based, with nomenclature A, B, C, and D (H70 only)

Pressure Class	Total Amount of Hydrogen in CHSS at 100% SOC (kg)	Water Volume of CHSS (L)	CHSS Capacity Category Identifier
H35	1.19 to 2.39	49.7 to 99.4	A
H35	2.39 to 4.18	99.4 to 174.0	B
H35	4.18 to 5.97	174.0 to 248.6	C
H70	2.00 to 4.00	49.7 to 99.4	A
H70	4.00 to 7.00	99.4 to 174.0	B
H70	7.00 to 10.00	174.0 to 248.6	C
H70	>10.00	>248.6	D

New in 2020 SAE J2601 to accommodate MD/HD vehicles

Overview – MC Formula: Communications

- MC Formula can be used with and without communications – same as Table-based
- Signals are the same

ID: Protocol Identifier

VN: Version Number

TV: Tank Volume

RT: Receptacle Type

FC: Fueling Command

MP: Measured Pressure

MT: Measured Temperature

OD: Optional Data

Overview – MC Formula: Process Limits

- **All General Requirements from Chapter 6 of SAE J2601 apply to MC Formula and Table-based protocols**
  - $T_{fuel\text{-}inst}$ >- 40 °C (always)
  - Do not start fill if initial pressure < 0.5 MPa or greater than nominal working pressure (35 or 70 MPa)
  - Station / CHSS pressure ≤ 87.5 MPa (always)
  - Mass flow rate ≤ 60 g/s
  - SOC ≤ 100%

- **Additional Requirements for both table-based and MC Formula**:
  - Keep station pressure within the pressure corridor
  - -40 °C ≤ T_{amb} ≤ 50 °C
  - SOC ≤ 100%
  - No more than 10 cycles
  - MAT_{30} ≤ -17.5 °C

Overview – MC Formula: Key Control Variables

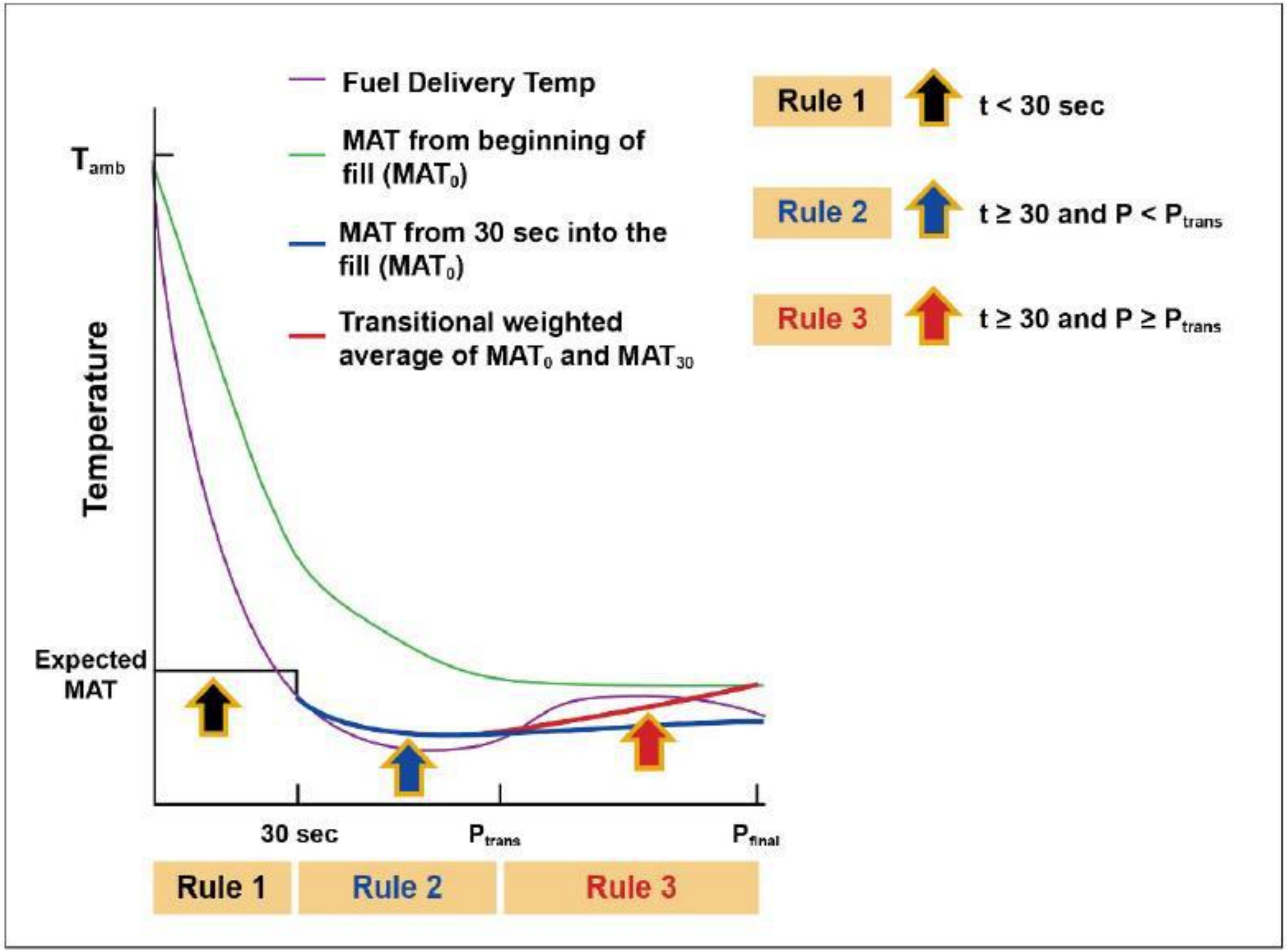
- Mass Average Fuel Delivery Temperature - **MAT**
- The time required to fill from minimum to maximum pressure under hot case conditions - t_{final}
- Variable Pressure Ramp Rate - **PRR**
- Target Pressure - P_{target}

- **MAT**, t_{final}, and **PRR** are calculated every second

$$MAT \rightarrow t_{final} \rightarrow PRR$$

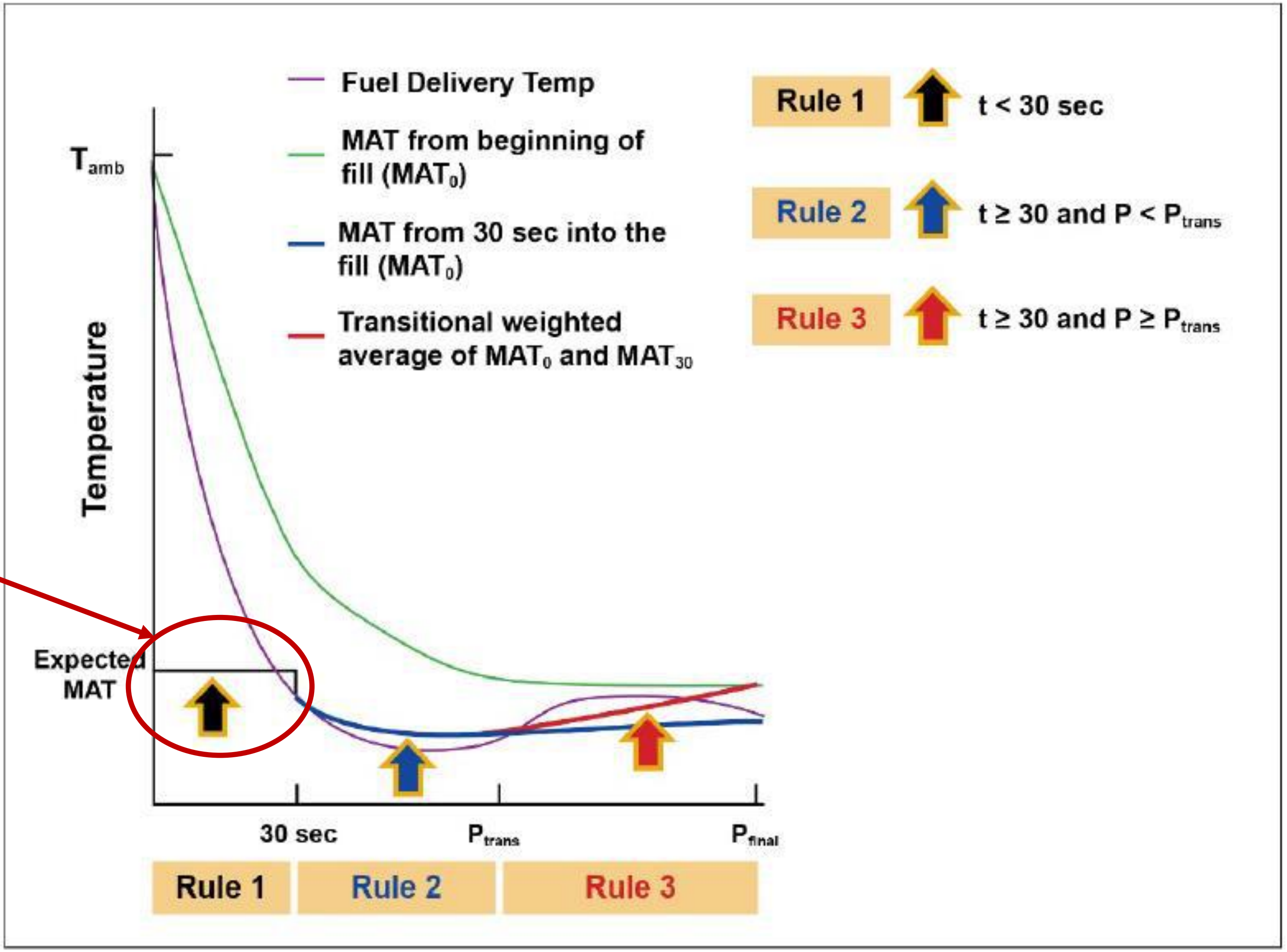
Overview – MC Formula: Rules for Calculating MAT

- MAT is very high at start of fill
  - Would cause large changes in ramp rate
- To reduce this effect MAT is broken into 3 rules
  - $MAT_{expected}$ – first 30 sec
  - MAT_{30} – calculated from 30 sec on
  - MAT_0 – calculated from beginning
  - MAT_C – the MAT value used for control – it is a function of the three rules



Overview – MC Formula: Rule 1 - Expected MAT

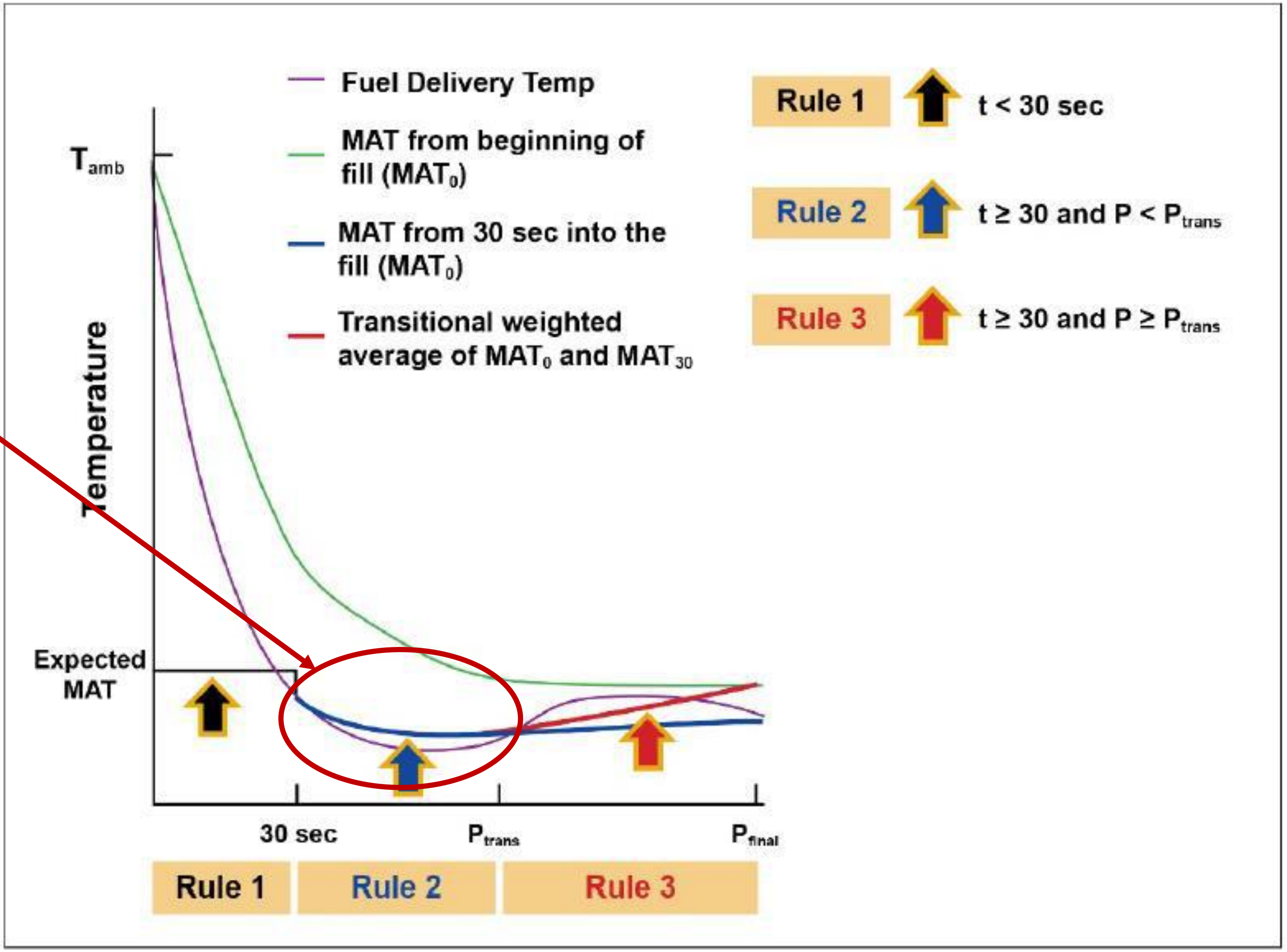
- t < 30 sec
- -36 °C ≤ $MAT_{expected}$ ≤ -17.5 °C
- $MAT_{expected}$ ≈ Expected value of MAT_0 at end of fill
- $MAT_{expected}$ is estimated by station designer



Overview – MC Formula: Rule 2 - MAT_{30}

- t > 30 sec and $P_{control} < P_{trans}$
  - P_{trans} is the pressure half way through fill
- MAT in this section is defined as MAT_{30}

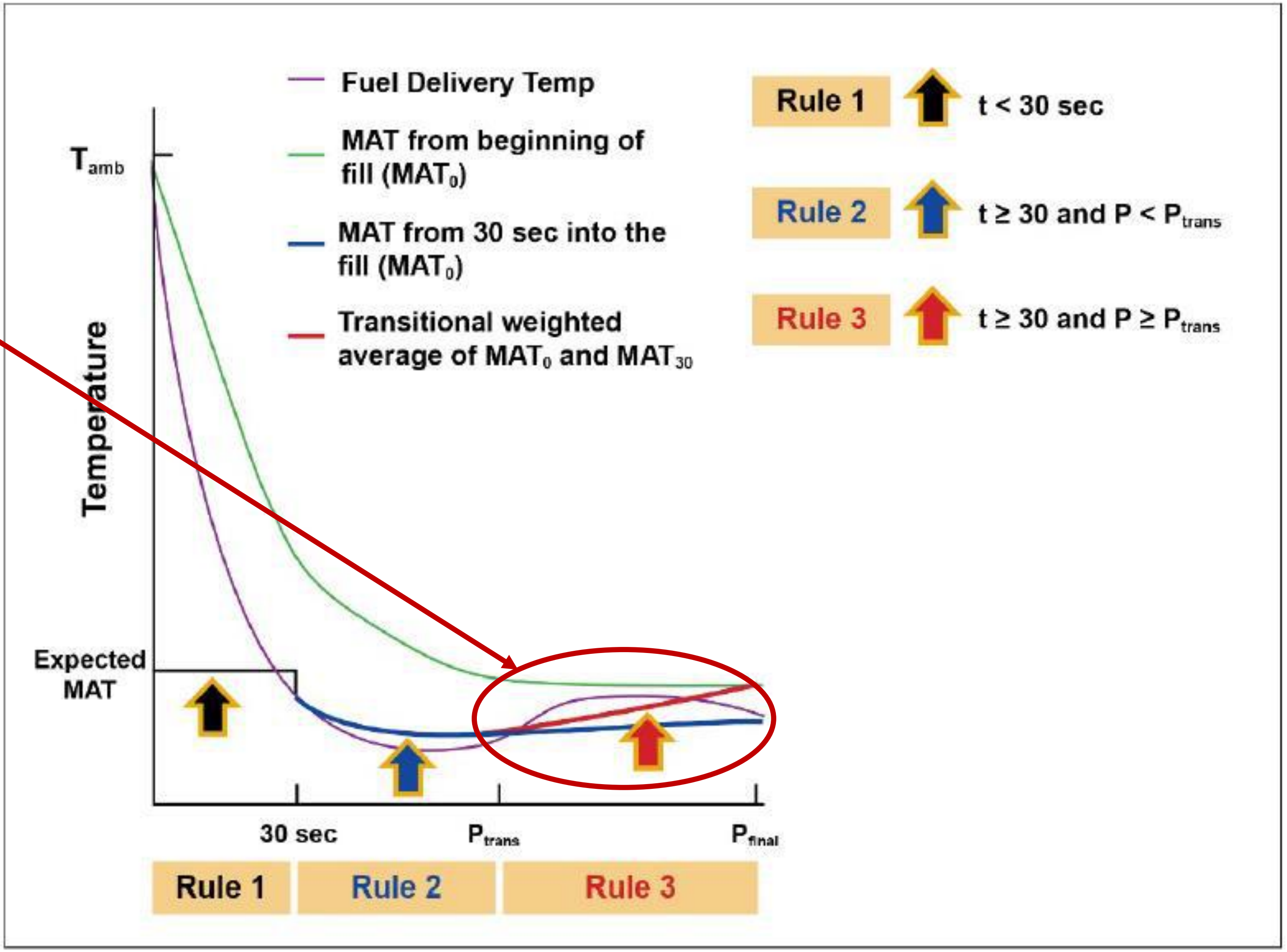
$$MAT_{30} = \frac{\sum_{30}^{j}[(m_{(j)} - m_{(j-1)}) \times 0.5(T_{fuel\_inst(j)} + T_{fuel\_inst(j-1)})]}{\sum_{30}^{j}(m_{(j)} - m_{(j-1)})}$$



Overview – MC Formula: Rule 3 – Transitional MAT

- t > 30 sec and $P_{control} > P_{trans}$
- MAT in this section is a transitionally weighted average of MAT_{30} and MAT_0
- The weighting function gradually increases the weighting from MAT_{30} to MAT_0
- At the end of the fill, the weighting is almost fully MAT_0

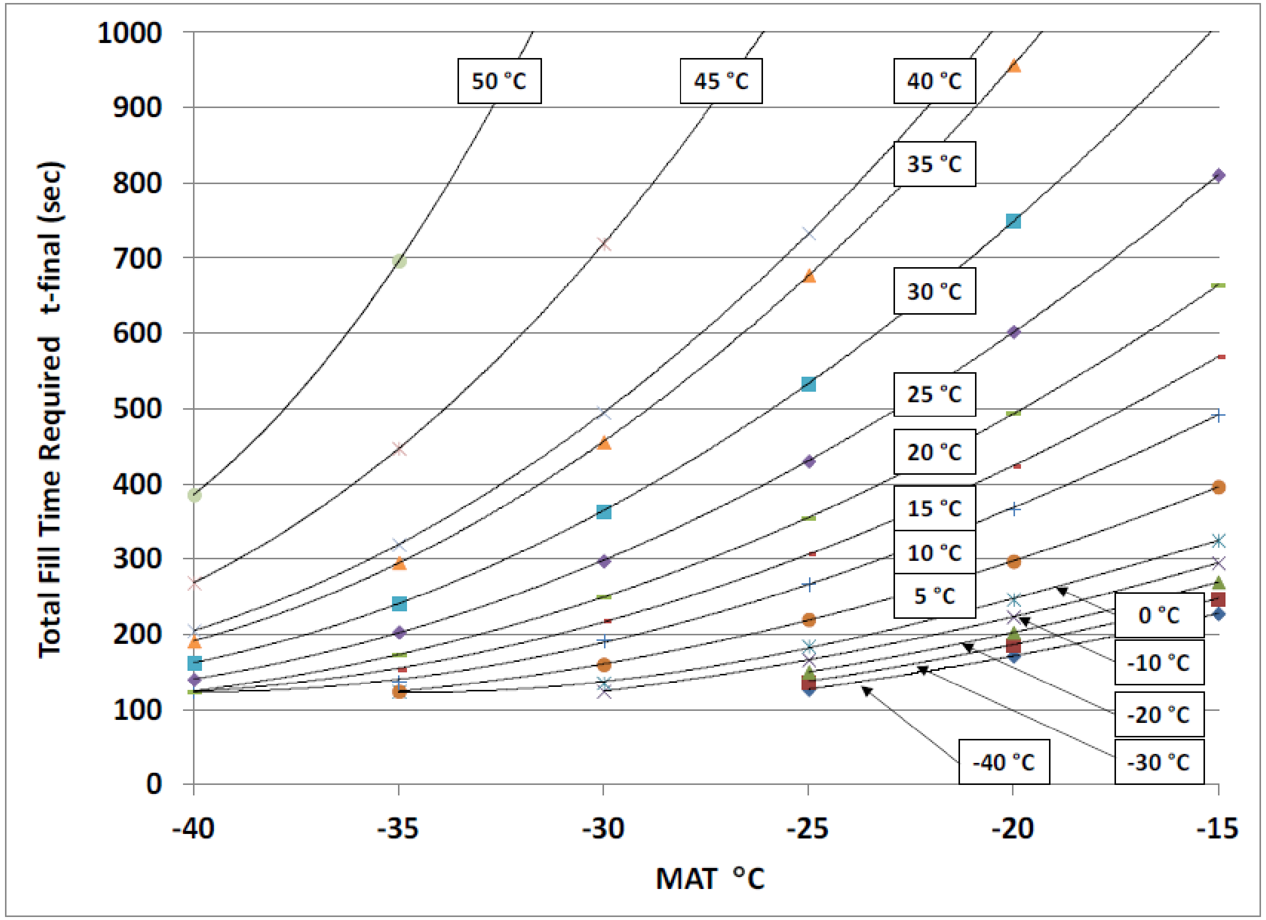
$$MAT_C = MAT_{30} \times \left(\frac{P_{final} - P_{control}}{P_{final} - P_{trans}}\right) + MAT_0 \times \left(1 - \frac{P_{final} - P_{control}}{P_{final} - P_{trans}}\right)$$



Overview – MC Formula: tfinal and MAT

- **t_{final} is the time required to fill from a minimum pressure to a maximum pressure under hot case conditions**
- **t_{final} is a function of the ambient temperature and the mass average of the fuel delivery temperature (MAT)**
- **t_{final} is derived using computer fueling simulations under hot case conditions**
- **As shown in the graph to the right, a polynomial equation can be drawn between the data points with a near perfect fit (R^2 > 0.999)**
- **This results in the following equation where a, b, c and d are derived using a best fit regression:**

$$t_{final} = a \times MAT^3 + b \times MAT^2 + c \times MAT + d$$



Overview – MC Formula: tfinal and MAT

The final equation for t_{final} is adjusted to account for real world variabilities

$$t_{final} = \alpha \times \beta \times [a \times MAT^3 + b \times MAT^2 + c \times MAT + d]$$

- α = Compensates for non-linearity of PRR
- β = Compensates for pressure tolerance
- a,b,c,d are stored in tables J1 – J16 in Appendix J of SAE J2601 (see example below):

Table J2 - Table of coefficients for 99.4 liter boundary CHSS with CD = FALSE and Pmin = 0.5

T_{amb} (°C / K)	a	b	c	d
50 / 323.15	1.1462427	-805.95758	188923.82	-14763290
45 / 318.15	0.12728894	-88.669728	20627.75	-1602334
40 / 313.15	0.01362863	-8.260816	1651.2	-108438
35 / 308.15	0.00459226	-1.80716	112.064	14112
30 / 303.15	0.000043	1.14407	-526.8	60268
25 / 298.15	0.00023559	0.7645	-383.873	45116.8
20 / 293.15	0.00202084	-0.72322	17.42	9783
15 / 288.15	0.00431385	-2.519	480.38	-29613.4
10 / 283.15	0.0023259	-1.12621	152.89	-3780
5 / 278.15	-0.00146812	1.58788	-497.62	48436
0 / 273.15	0.00411881	-2.69214	590.798	-43511
-10 / 263.15	0.00337783	-2.15258	458.639	-32638.6
-20 / 253.15	-0.0035514	3.035924	-837.335	75323
-30 / 243.15	0.0055517	-3.842547	893.505	-69736
-40 / 233.15	0.0035207	-2.346046	525.1	-39448

Overview – MC Formula: Variable Pressure Ramp Rate

The lookup tables in SAE J2601 provide values for APRR. APRR can be defined in the terms below.

$$APRR = \frac{P_{final} - P_{min}}{t_{final}}$$

- P_{final} = maximum pressure for hot case conditions
- P_{min} = minimum pressure for hot case conditions
- t_{final} = time required to fill from minimum to maximum pressure under hot case conditions

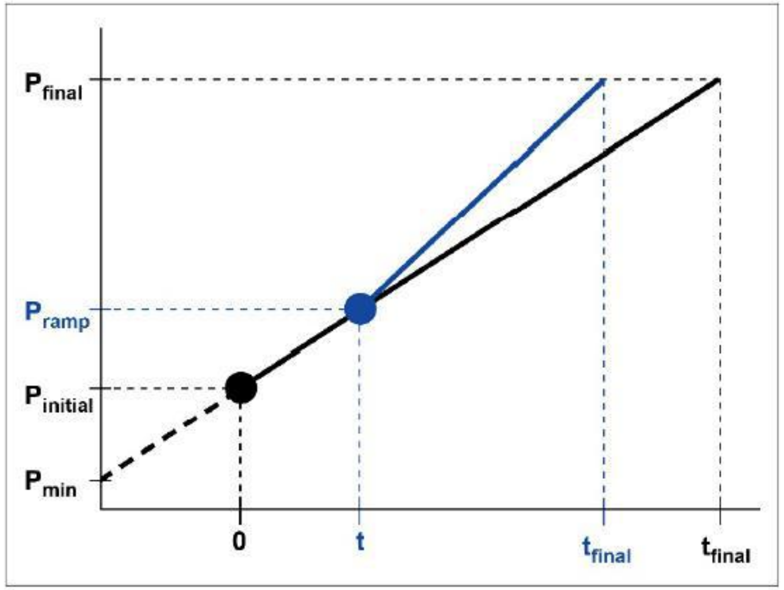
With the lookup table, APRR doesn't change during the fill, which means that t_{final} is a constant value.

However, with MC Formula, t_{final} does change during the fill as MAT varies. Therefore, we need a different equation.

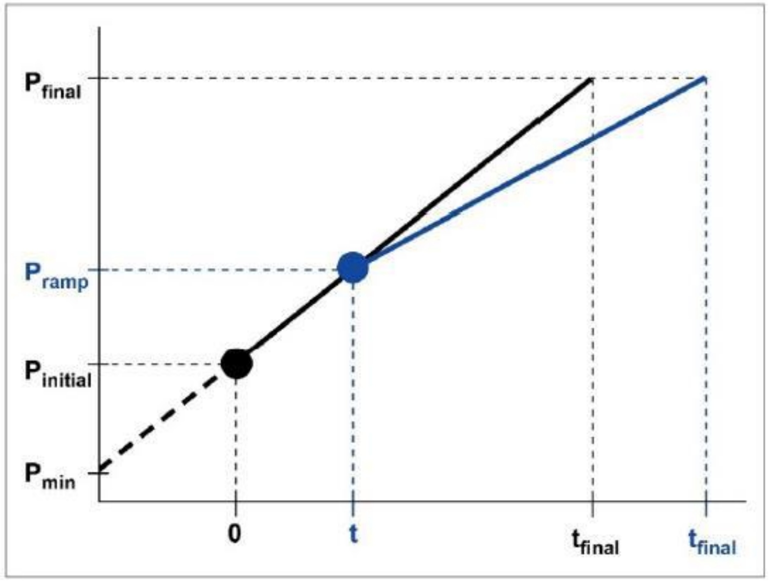
$$PRR = \frac{P_{final} - P_{ramp}}{t_{final} \times \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{min}} \right) - t}$$

P_{ramp} = the pressure at time t
$P_{initial}$ = the pressure at the beginning of the fill

t_{final} decreasing



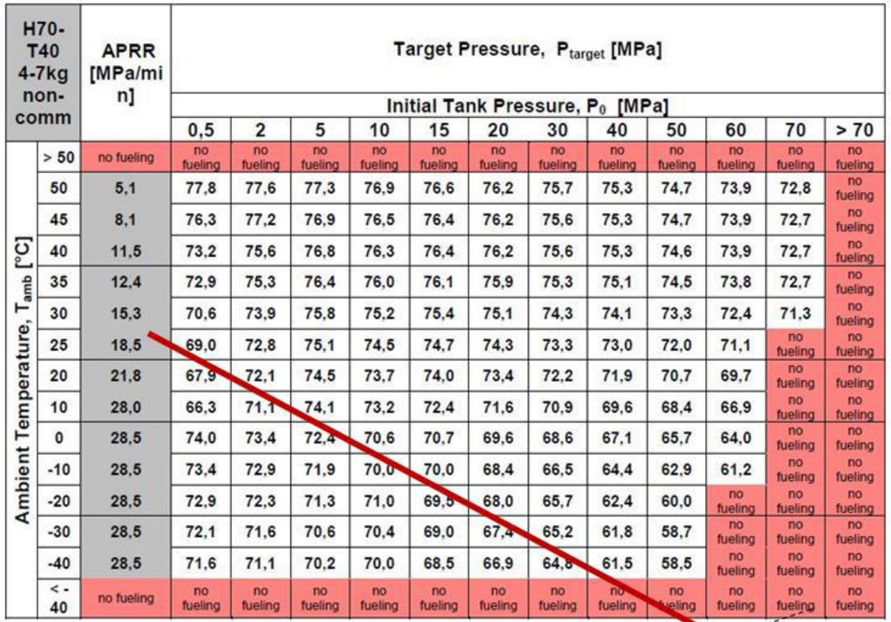
t_{final} increasing



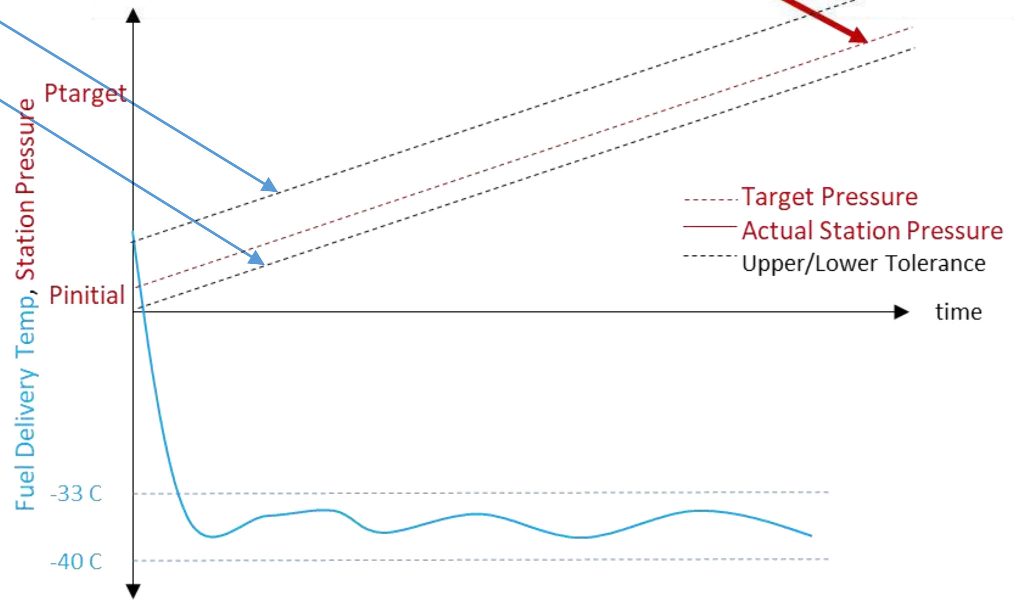
Overview – MC Formula: Pressure Corridor

Table Based has a pressure tolerance

- Upper Tolerance +7.0 MPa
- Lower Tolerance -2.5 MPa



H70-T40 4-7kg non-comm		APRR [MPa/min]	Target Pressure, P_{target} [MPa] — Initial Tank Pressure, P_0 [MPa]: 0,5	2	5	10	15	20	30	40	50	60	70	> 70
Ambient Temperature, T_{amb} [°C]	> 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	76,2	75,7	75,3	74,7	73,9	72,8	no fueling
	45	8,1	76,3	77,2	76,9	76,5	76,4	76,2	75,6	75,3	74,7	73,9	72,7	no fueling
	40	11,5	73,2	75,6	76,8	76,3	76,4	76,2	75,6	75,3	74,6	73,9	72,7	no fueling
	35	12,4	72,9	75,3	76,4	76,0	76,1	75,9	75,3	75,1	74,5	73,8	72,7	no fueling
	30	15,3	70,6	73,9	75,8	75,2	75,4	75,1	74,3	74,1	73,3	72,4	71,3	no fueling
	25	18,5	69,0	72,8	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	74,5	73,7	74,0	73,4	72,2	71,9	70,7	69,7	no fueling	no fueling
	10	28,0	66,3	71,1	74,1	73,2	72,4	71,6	70,9	69,6	68,4	66,9	no fueling	no fueling
	0	28,5	74,0	73,4	72,4	70,6	70,7	69,6	68,6	67,1	65,7	64,0	no fueling	no fueling
	-10	28,5	73,4	72,9	71,9	70,0	70,0	68,4	66,5	64,4	62,9	61,2	no fueling	no fueling
	-20	28,5	72,9	72,3	71,3	71,0	69,5	68,0	65,7	62,4	60,0	no fueling	no fueling	no fueling
	-30	28,5	72,1	71,6	70,6	70,4	69,0	67,4	65,2	61,8	58,7	no fueling	no fueling	no fueling
	-40	28,5	71,6	71,1	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

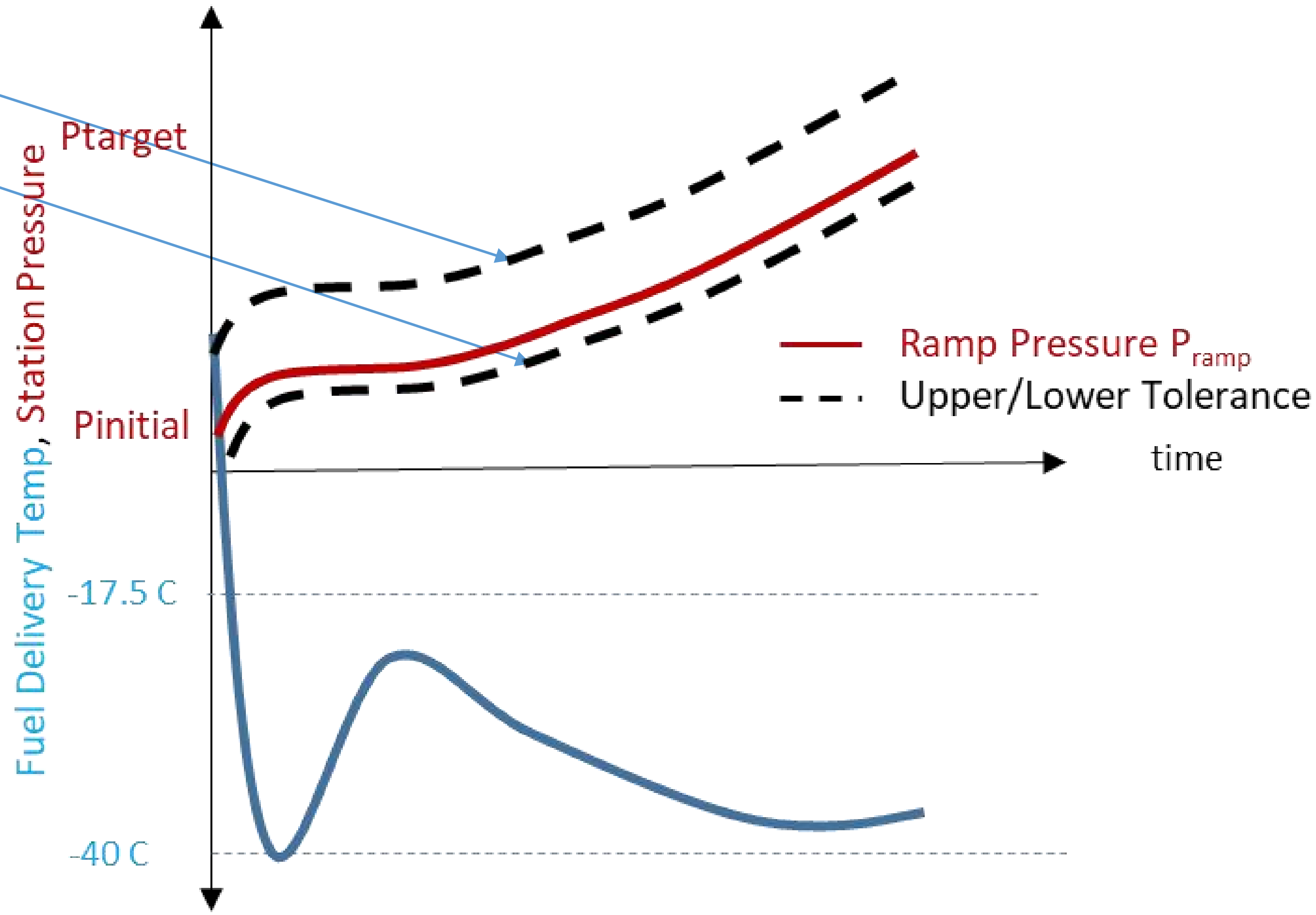


Overview – MC Formula: Pressure Corridor

MC Method has the same tolerance

- Upper Tolerance +7.0 MPa
- Lower Tolerance -2.5 MPa

- Tolerance limits stay constant, but follow the ramp pressure which varies with PRR



Overview – MC Formula: End of Fill Determination

Table-Based Approach

- Non-Communication Fill
  - Non-Communication Target Pressure in tables
  - 100% Cold Case SOC
- Communication Fill Primary
  - SOC= 95-100% using MT
- Communication Secondary
  - Communication Target Pressure in tables
  - These values typically result in limiting SOC to < 115% Cold Case SOC (in the case that the MT value from the vehicle is wrong)

H70-T40 4-7kg non-comm		APRR [MPa/min]	Target Pressure, P_{target} [MPa]											
			Initial Tank Pressure, P_0 [MPa]											
			0,5	2	5	10	15	20	30	40	50	60	70	> 70
Ambient Temperature, T_{amb} [°C]	> 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	76,2	75,7	75,3	74,7	73,9	72,8	no fueling
	45	8,1	76,3	77,2	76,9	76,5	76,4	76,2	75,6	75,3	74,7	73,9	72,7	no fueling
	40	11,5	73,2	75,6	76,8	76,3	76,4	76,2	75,6	75,3	74,6	73,9	72,7	no fueling
	35	12,4	72,9	75,3	76,4	76,0	76,1	75,9	75,3	75,1	74,5	73,8	72,7	no fueling
	30	15,3	70,6	73,9	75,8	75,2	75,4	75,1	74,3	74,1	73,3	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	74,5	73,7	74,0	73,4	72,2	71,9	70,7	69,7	no fueling	no fueling
	10	28,0	66,3	71,1	74,1	73,2	72,4	71,6	70,9	69,6	68,4	66,9	no fueling	no fueling
	0	28,5	74,0	73,4	72,4	70,6	70,7	69,6	68,6	67,1	65,7	64,0	no fueling	no fueling
	-10	28,5	73,4	72,9	71,9	70,0	70,0	68,4	66,5	64,4	62,9	61,2	no fueling	no fueling
	-20	28,5	72,9	72,3	71,3	71,0	69,5	68,0	65,7	62,4	60,0	no fueling	no fueling	no fueling
	-30	28,5	72,1	71,6	70,6	70,4	69,0	67,4	65,2	61,8	58,7	no fueling	no fueling	no fueling
	-40	28,5	71,6	71,1	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

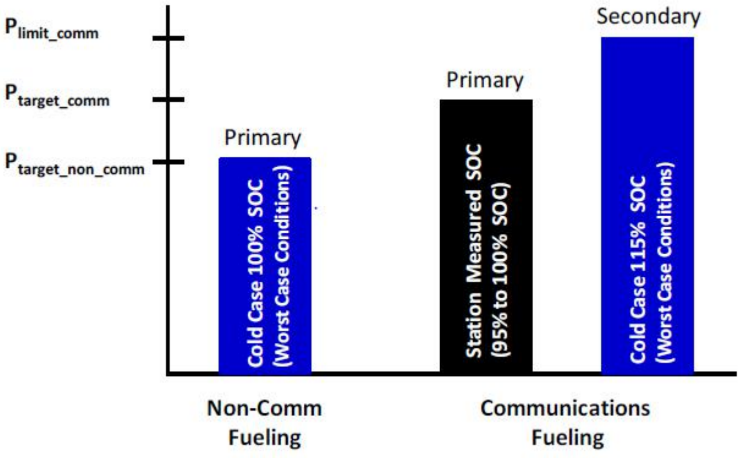


Figure H14 - Illustration of Pressure Targets and Limits for Ending Pressure Control

Overview – MC Formula: End of Fill Determination

MC Formula Approach

- Option 1: Use the MC Method
  (See Next Slide)

- Option 2: Ending Pressure Tables
  - Non-Comm
  - Communication Fill Primary
    - Pressure target based on 95-100% SOC using MT
  - Communication Fill Secondary
    - Pressure Limit
    - These values typically result in limiting SOC to < 115% Cold Case SOC (in the case that the MT value from the vehicle

Table K3 – MC Formula Non-Communication Pressure Targets (H70-T40, CHSS Capacity Category C)

H70-T40 CHSS Capacity Category C Non-Comm	MC Formula - Target Pressure, $P_{target\_non\_comm}$ [MPa]										
	Initial Tank Pressure, $P_{initial}$ [MPa]										
Ambient Temperature, T_{amb} [°C]	< 5 No interpolation	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
50	78.3	78.3	77.7	77.2	77.1	76.3	75.8	75.1	74.2	72.8	no fueling
45	77.8	78.1	77.6	77.0	77.2	76.4	76.0	75.1	74.2	72.8	no fueling
40	77.6	77.9	77.3	76.7	77.0	76.2	75.9	75.0	74.2	72.7	no fueling
35	77.0	77.4	76.8	76.2	76.6	75.8	75.6	74.8	74.0	72.7	no fueling
30	76.3	76.7	76.0	76.2	75.7	74.8	74.5	73.6	72.7	71.3	no fueling
25	75.5	75.9	75.2	75.3	74.8	73.7	73.4	72.3	71.3	no fueling	no fueling
20	74.8	75.0	74.1	74.3	73.7	72.5	72.1	71.0	69.9	no fueling	no fueling
10	73.1	73.1	72.0	72.3	71.6	70.8	69.6	68.6	67.0	no fueling	no fueling
0	71.6	71.6	71.2	70.2	69.4	68.4	67.1	65.8	64.1	no fueling	no fueling
-10	70.9	70.9	70.4	69.1	67.7	66.0	64.4	63.0	61.2	no fueling	no fueling
-20	70.2	70.2	69.7	68.4	67.1	64.9	62.0	60.1	no fueling	no fueling	no fueling
-30	69.3	69.3	68.9	67.7	66.3	64.3	61.4	58.5	no fueling	no fueling	no fueling
-40	68.8	68.8	68.4	67.2	65.9	63.9	61.1	58.4	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

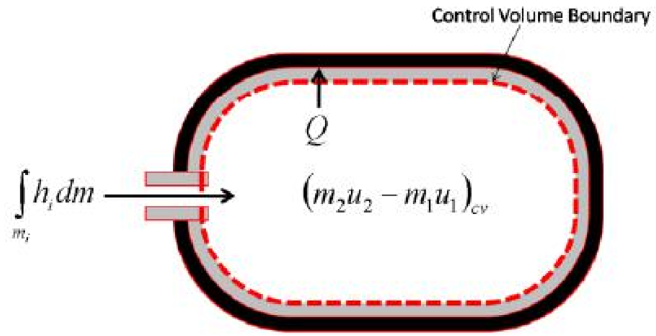
Table K30 – MC Formula Communication Pressure Limits (H70-T40, CHSS Capacity Category C)

H70-T40 CHSS Capacity Category C Comm	MC Formula - Communication Pressure Limit, P_{limit_comm} [MPa]										
	Initial Tank Pressure, $P_{initial}$ [MPa]										
Ambient Temperature, T_{amb} [°C]	< 5 No interpolation	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
50	83.5	83.5	86.9	86.6	86.3	85.6	84.7	83.7	82.5	81.0	no fueling
45	83.5	83.5	87.0	86.7	86.2	85.2	84.1	82.8	81.4	79.6	no fueling
40	83.5	83.5	87.0	86.4	85.9	84.6	83.3	81.8	80.2	78.2	no fueling
35	83.5	83.5	87.0	86.4	85.9	84.6	83.2	81.7	80.1	78.2	no fueling
30	83.5	83.5	86.9	86.3	85.6	84.2	82.6	81.0	79.2	77.2	no fueling
25	83.5	83.5	86.8	86.0	85.3	83.7	82.0	80.2	78.3	76.1	no fueling
20	83.5	87.1	86.4	85.5	84.7	83.0	81.2	79.3	77.4	75.0	no fueling
10	83.5	86.6	85.7	84.8	83.9	82.0	80.0	78.0	75.9	73.4	no fueling
0	83.5	85.7	84.6	83.4	82.3	80.0	77.7	75.4	72.9	no fueling	no fueling
-10	83.5	85.5	84.4	83.2	82.1	79.8	77.5	75.2	72.8	no fueling	no fueling
-20	83.5	85.3	84.2	83.0	81.9	79.6	77.3	75.0	72.6	no fueling	no fueling
-30	83.5	85.0	83.9	82.8	81.7	79.4	77.1	74.8	72.4	no fueling	no fueling
-40	83.5	84.8	83.7	82.6	81.4	79.2	76.9	74.6	72.3	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

Overview – MC Formula: End of Fill Determination

MC Method Ending Pressure Control

- The MC Method is an analytical method based on a **lumped heat capacity model**, which utilizes a thermodynamic characterization of a compressed hydrogen storage vessel.
- The characterization is described by **MC, which is a parameter that quantifies the capability of the hydrogen storage vessel to absorb the heat generated during fueling**, expressed in terms of kJ/K.
- **MC is an equation which is a function of initial conditions, fueling conditions, and the fueling time**.
- By calculating MC, along with initial CHSS pressure and temperature, and the **measurement of enthalpy and mass flow at the dispenser outlet** throughout the fill, the end of fill gas temperature in the storage vessel can be calculated, from which a target pressure can be calculated.



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

$$MC = AC + BC \times \ln\sqrt{\frac{U_{adiabatic}}{U_{initial}}} + GC \times (1 - e^{-KC \times \Delta t})^{JC}$$

The MC Method calculates the "cold case" gas temperature T_{cold} (shown as T_{final} in the equations above). This gas temperature is then used in the equation below to calculate a non-communication Pressure Target and a communication fill Pressure Limit

$$P_{target\_non\_comm} = 0.2782 \times T_{cold} - 4.7145E-05 \times T_{cold}^2 - 6.18$$

$$P_{limit\_comm} = MINIMUM\,[83.5,\ (0.3457 \times T_{cold} - 6.6942E-05 \times T_{cold}^2 - 7.29)]$$

Outline

- Background
- Overview of the MC Formula Protocol
- **MC Formula Validation Calculator**
- MC Formula Protocol Validation (CSA HGV 4.3)
- Usage of MC Formula Protocol in the United States
- Conclusion

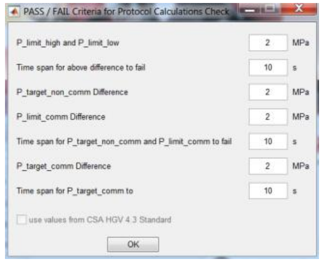
MC Formula: Validation Calculator (MCFVC)

The Tool is programmed in MATLAB, but it is an executable Windows File which can run on any PC

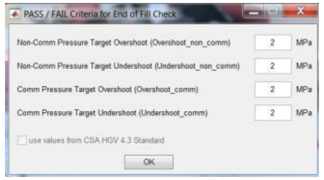
Station Data File Loaded Here

HDTA Data File Loaded Here

PASS / FAIL Criteria for Protocol Function

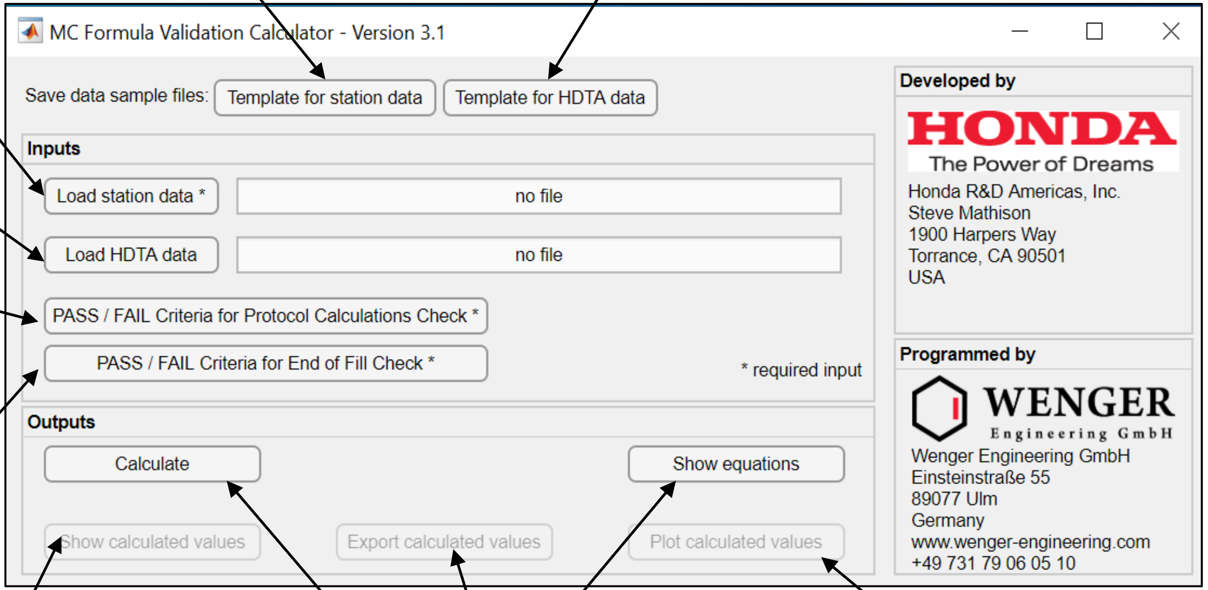


PASS / FAIL Criteria End of Fill Check



Station Data Template

HDTA Data Template



Initiates Calculations

Shows Equations

Shows Calculated Values

Exports Calculated Values & Station Values

Plots Calculated Values & Station Values

There are two versions of the MCFVC – V2.3 aligns with the 2016 SAE J2601 and V3.1 aligns with the 2020 SAE J2601

MCFVC is available for free here → https://www.wenger-engineering.de/mc-formula-validation-calculator-login/

MC Formula: Validation Calculator (MCFVC)

<u>The MCFVC can be used in the following ways</u>:

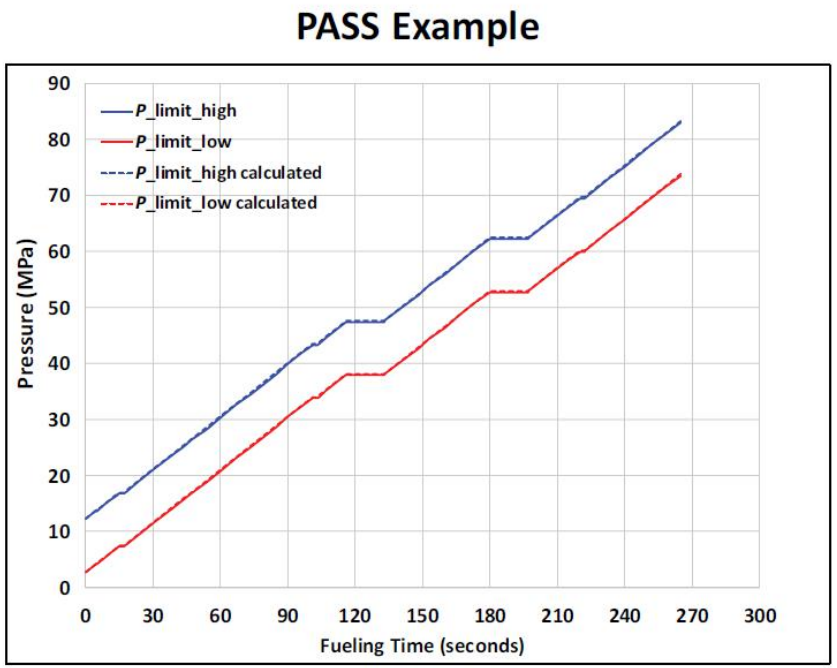
- By the H2 Dispenser Manufacturer to assist during programming of the PLC – can check PLCs values against MCFVC
- By a testing agency to validate compliance with a validation standard such as CSA HGV 4.3

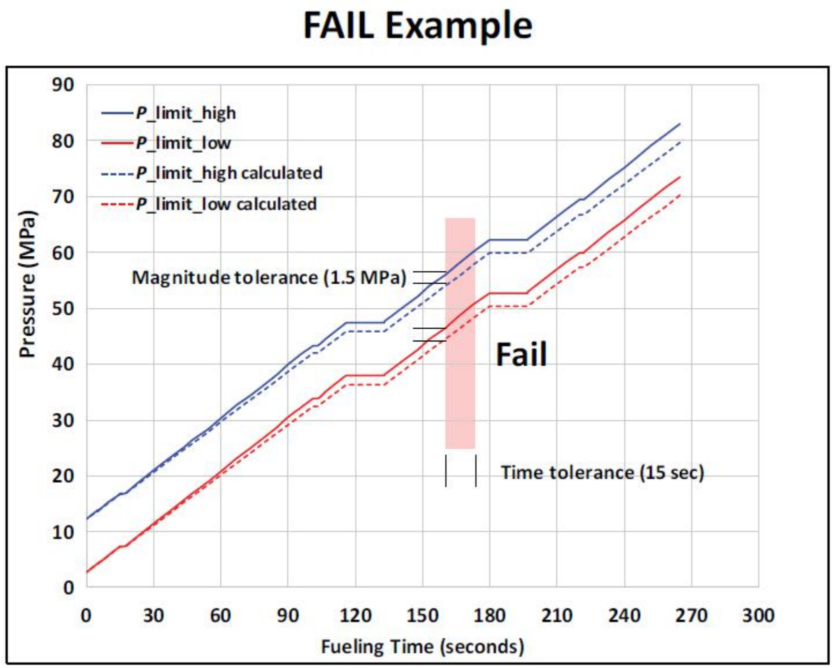
<u>The MCFVC automatically checks</u>:

- **Protocol function →** ensures that control parameters are calculated correctly
- **Process Limits →** ensures that the station stays within and/or responds appropriately to the process limits

MC Formula: Validation Calculator (MCFVC)

Protocol Function – Pressure Corridor



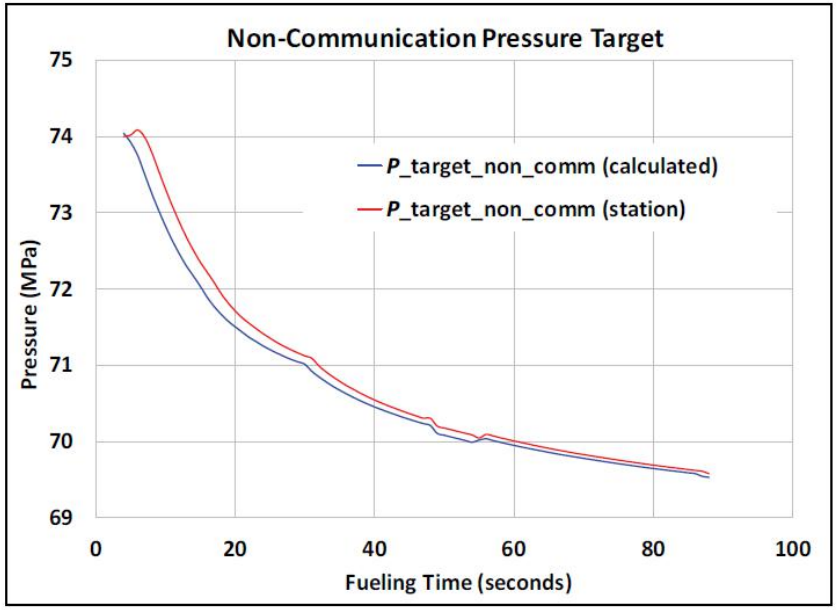


- The MCFVC compares the station’s recorded values of the upper and lower pressure limits to the calculator's values
- The comparison is made on both a magnitude and time basis, both of which can be set by the user.
- In the HGV 4.3 validation standard, the PASS criteria is that the absolute value of the difference between the station value and calculator value shall not exceed 1.5 MPa for 15 consecutive seconds

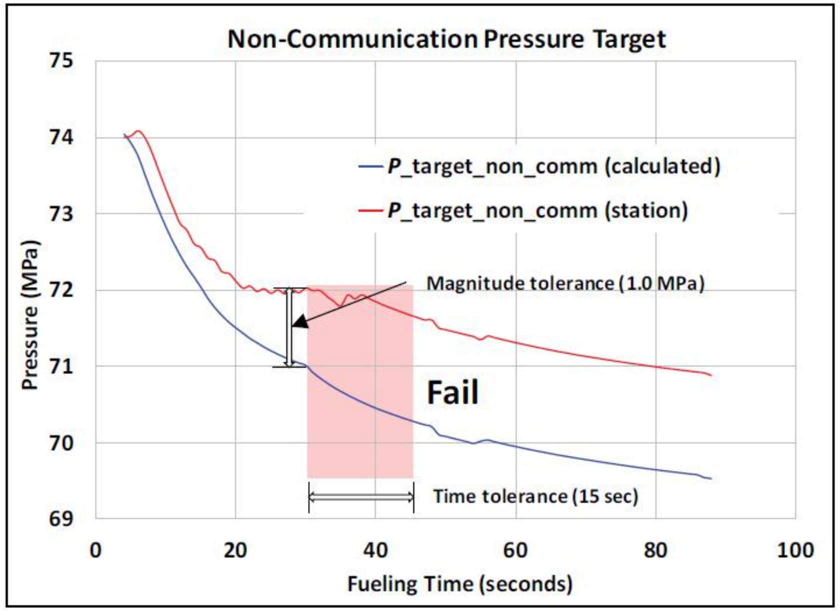
MC Formula: Validation Calculator (MCFVC)

Protocol Function – Pressure Target

PASS Example

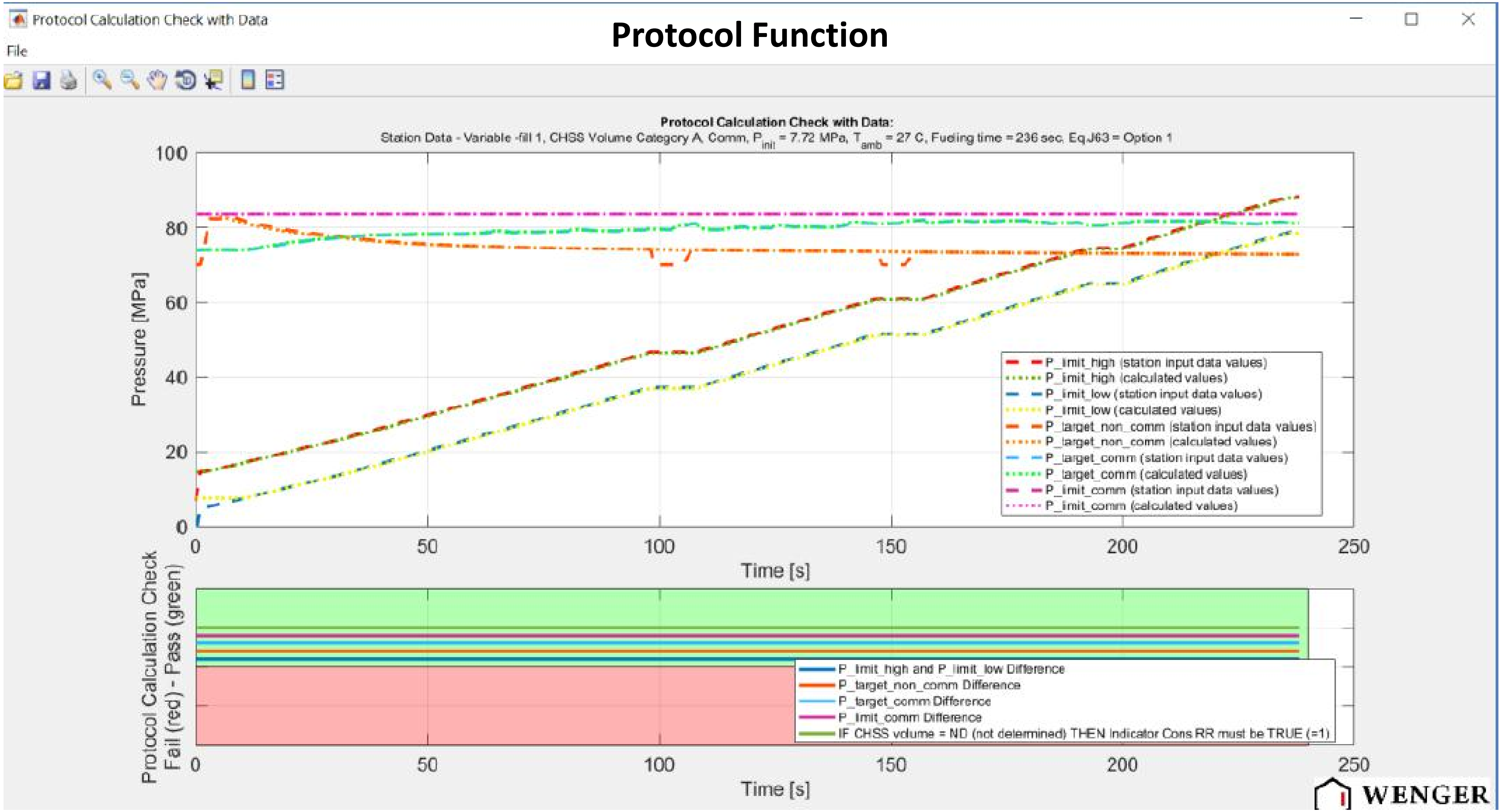


FAIL Example



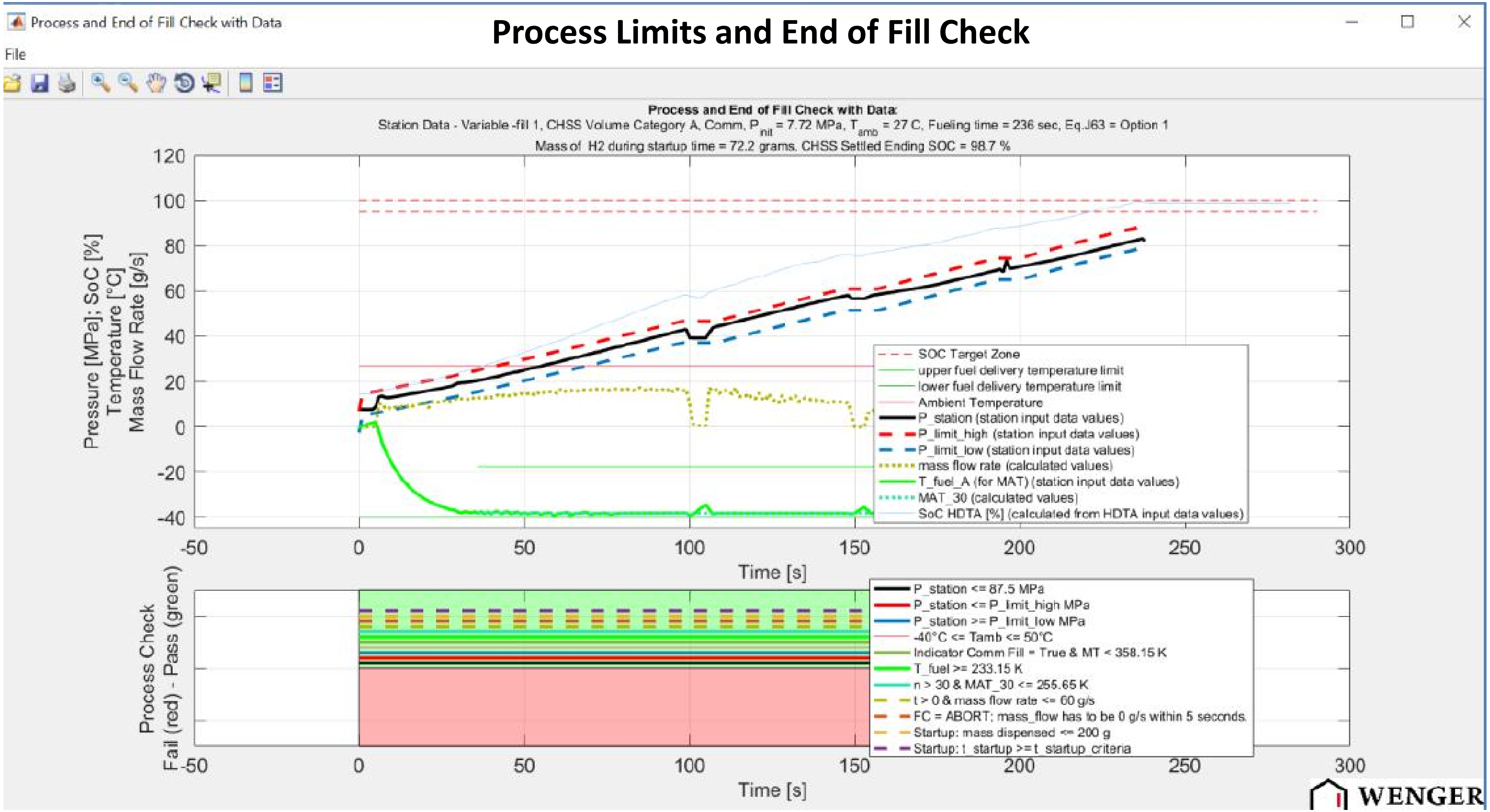
- The MCFVC compares the station's recorded value of the calculator's value
- The comparison is made on both a magnitude and time basis, both of which can be set by the user.
- In the HGV 4.3 validation standard, the PASS criteria is that the absolute value of the difference between the station value and calculator value shall not exceed 1.0 MPa for 15 consecutive seconds

MC Formula: Validation Calculator (MCFVC)



If the lines in the bottom plot stay in the green region it indicates PASS. If the lines go into the red region, it indicates FAIL

MC Formula: Validation Calculator (MCFVC)



If the lines in the bottom plot stay in the green region it indicates PASS. If the lines go into the red region, it indicates FAIL

Outline

- Background
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MC Formula: Protocol Validation – HGV 4.3

MC Formula Protocol Validation Approach

Validation has three parts (excluding communications specific testing):

Protocol Check

Define tolerances for:

a) Pressure Corridor

b) Pressure Targets

To PASS, the station must calculate these parameters correctly (within tolerance)

Fault Response Check

Fault response defined in J2601:

- Check that the dispenser responds correctly to "fault" conditions

To PASS, the station must stop the fill within 5 sec if a process check fails (i.e falls outside allowed limits)

Fueling Evaluation

Check fill performance,

1. Fills complete with no fault conditions
2. Ending @ P-targets and SOC

To PASS, the station must stay within the process limits and ending SOC within target range

"FAT or SAT" (Protocol Check and Fault Response Check)
With FAT, tests are conducted on representative system in lab or factory

"SAT only" (Fueling Evaluation)
Conducted at the site
Limited set of tests

MC Formula: Protocol Validation – HGV 4.3

CSA/ANSI HGV 4.3:19 (current version): Test methods for hydrogen fueling parameter evaluation

HGV 4.3 is currently under revision to align it with the 2020 SAE J2601 and to allow more robust FAT approach

Overview of Testing:

The testing for a dispenser to meet SAE J2601 MC formula-based fueling protocol includes four key areas:

- **fault testing** to verify the station reacts properly to out-of-bounds conditions;
- **communication tests** that confirm the proper operation of the vehicle (or test apparatus) to station communication system;
- **protocol function tests** to verify the station properly calculates the control parameters; and
- **fueling evaluation tests** to verify that the station can successfully complete fills while keeping all process parameters in bounds and achieving end of fill targets.

Green *= provision for FAT*
Blue *= SAT only*

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- Conclusion

MC Formula: Usage in the US (list of public stations in CA)

Location	Operator
Anaheim, CA	Air Liquide
Campbell, CA	First Element Fuel
Citrus Heights, CA	Shell
Costa Mesa, CA	First Element Fuel
Del Mar, CA	First Element Fuel
Diamond Bar, CA	Air Products
Emeryville, CA	Messer
Fairfax – LA, CA	Air Products
Fountain Valley, CA	First Element Fuel
Fremont, CA	First Element Fuel
Harris Ranch, CA	First Element Fuel
Hayward, CA	First Element Fuel
Hollywood, CA	First Element Fuel
La Canada Flintridge, CA	First Element Fuel

Location	Operator
Lake Forest, CA	First Element Fuel
Lake Tahoe – Truckee, CA	First Element Fuel
Lawndale, CA	Air Products
LAX	Air Liquide
Long Beach, CA	First Element Fuel
Mill Valley	First Element Fuel
Mission Hills, CA	First Element Fuel
Mountain View, CA	Iwatani
Oakland, CA	First Element Fuel
Palo Alto, CA	Air Liquide
Playa Del Rey, CA	First Element Fuel
Sacramento, CA	Shell
San Francisco – Harrison St.	Shell
San Francisco – Mission St.	Shell

Location	Operator
San Francisco – Third St.	Shell
San Jose, CA	First Element Fuel
San Juan Capistrano, CA	Iwatani
San Ramon, CA	Iwatani
Santa Barbara, CA	First Element Fuel
Santa Monica, CA	Air Products
Saratoga, CA	First Element Fuel
South Pasadena, CA	First Element Fuel
South San Francisco, CA	First Element Fuel
Thousand Oaks, CA	First Element Fuel
Torrance, CA	Shell
UC Irvine, CA	Air Products
West Sacramento, CA	Iwatani
Woodland Hills, CA	Air Products

→ Stations using MC Formula

27 out of a total 42 retail public stations (~65%) in California use the MC Formula protocol

Outline

MC Formula: Conclusion

General:

- MC Formula and Table-based protocols are **both standard protocols within SAE J2601**
- MC Formula offers significantly **better fueling performance** than table-based due primarily to **its direct use of the fuel delivery temperature**
- MC Formula also **allows the station more flexibility** (no fallback or step changes between "T" categories)

Overview of MC Formula:

- Almost all requirements are the same for table-based and MC Formula;
- Both MC Formula and table-based are **based on the same set of assumptions and boundary conditions**
- Both MC Formula and table-based can be **used with and without communications**, and have a **cold dispenser option**

MC Formula Validation Calculator:

- A **freely available software tool** that is very useful for dispenser programming and station validation

MC Formula Protocol Validation:

- The CSA HGV 4.3 standard provides validation requirements for both table-based and MC Formula protocols
- CSA HGV 4.3 is under revision to align with the 2020 SAE J2601 and to provide a more rigorous FAT option
- MC Formula validation consists of **fault testing, communications testing, protocol function testing** and **fueling evaluation**

MC Formula Usage in the United States:

- Almost **65% of public retail stations in California utilize MC Formula**
- At least **four dispenser manufacturers offer dispensers capable of using the MC Formula protocol**

Acknowledgement and Contact

Acknowledgement:

The development of the MC Formula fueling protocol was supported by Honda R&D Americas LLC.

A special thanks to the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office, within the Office of Energy Efficiency and Renewable Energy for supporting my participation this workshop and ongoing support for my work in standards development organizations.

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Contact:

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

Notice:

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