MC Formula
Technical Overview

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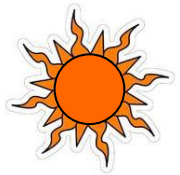
Overview – Worst Case Boundary Conditions

Hot Case

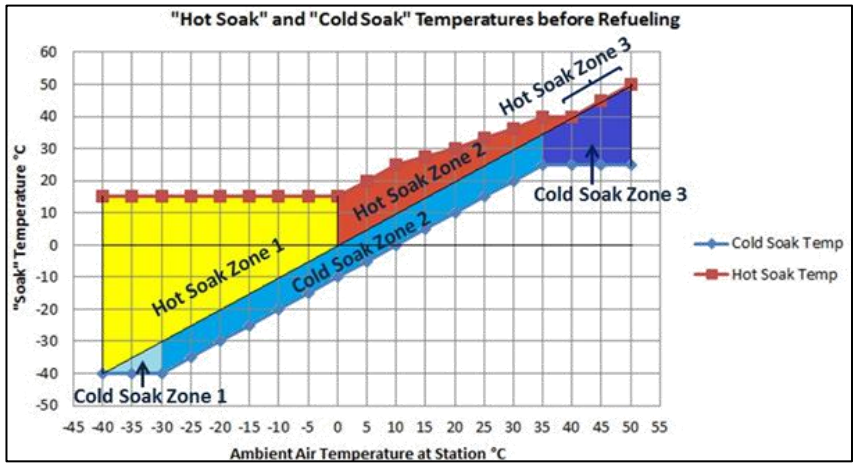
Because gas temperature in the tank is unknown, worst case assumptions must be used

Cold Case



Hot Soak
Park in the hot sun in summer or in heated garage during winter

Hot Tank "Type 4" Plastic Liner + **Tank is at minimum pressure**



Cold Soak
Park in the A/C garage

+ Defueling
Drive high speed on autobahn (rapid defueling)

Cold Tank Small "Type 3" Aluminum Liner

All Vehicle Fuelings Fall Within This Range of Boundary Conditions

Hotter ending gas temperature ⇐ **Absorbs Heat Less** — **Absorbs Heat More** ⇒ **Colder ending gas temperature**

To Prevent Overheating:
Pressure Ramp Rate determined by Hot Case Boundary Conditions

To Prevent Overfilling:
End-of-fill pressure target determined by Cold Case

Overview – Pressure Ramp Rate & Ending

Pressure Ramp Rate

Hot Case Boundary Conditions

Vehicle Components *J2601 (Appendix A)*

Reference Pressure Drop *J2601 (Appendix A)*

Type IV (2, 4, 7, 10kg) *J2601 (Appendix A)*

Station Components *J2601 (Appendix A)*

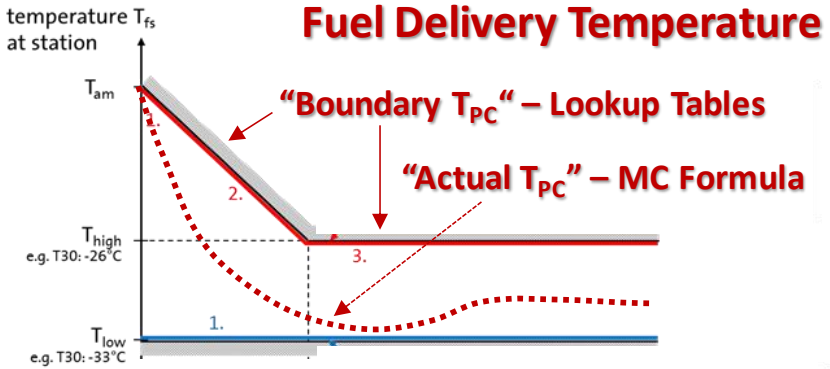
Hot Case

Initial Pressure Assumptions *J2601 (Appendix A)*

Hot Soak Assumptions *J2601 (Appendix A)*

+

Fuel Delivery Temperature



Ending Pressure

Cold Case Boundary Conditions

Vehicle Components *J2601 (Appendix A)*

Reference Pressure Drop *J2601 (Appendix A)*

Type III (1 kg H35 / H70) *J2601 (Appendix A)*

Station Components *J2601 (Appendix A)*

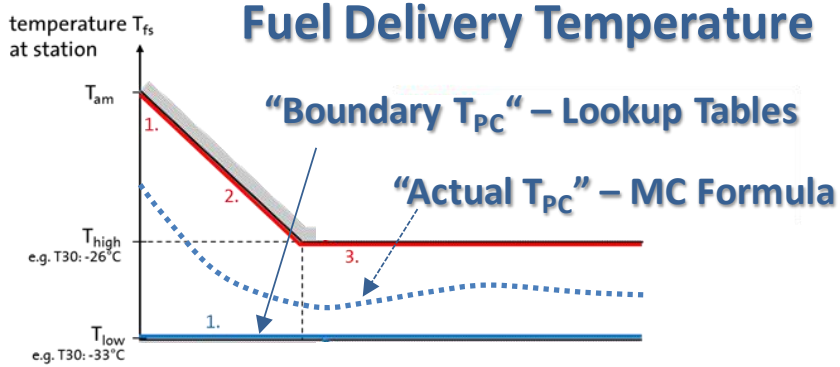
Cold Case

SOC Limits (Comm & Non-Comm) *J2601 (Appendix A)*

Cold Soak / Defuel Assumptions *J2601 (Appendix A)*

+

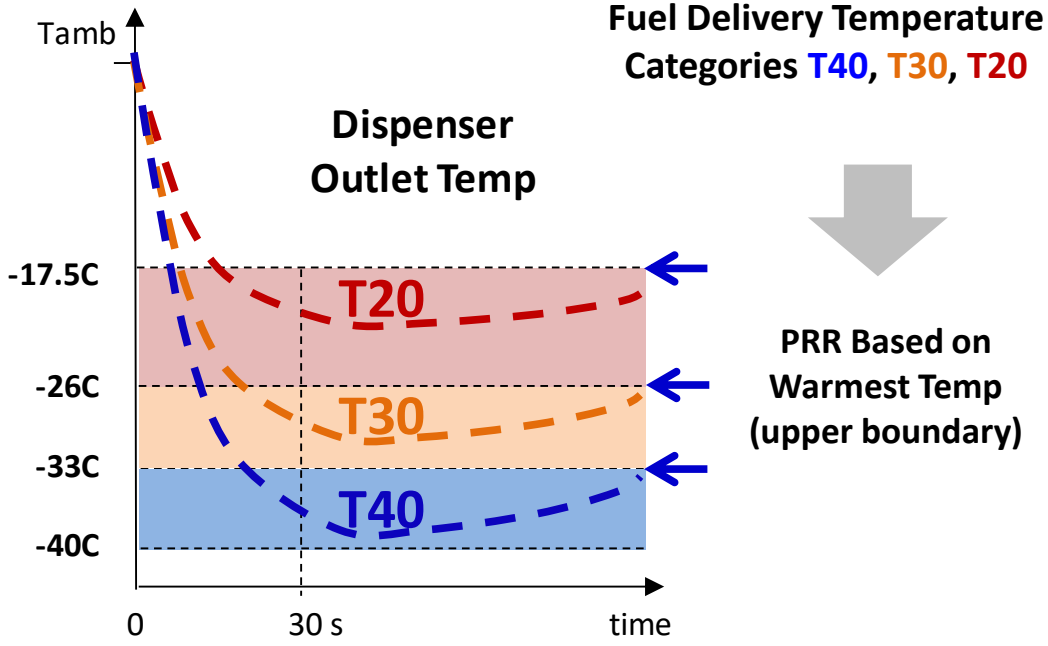
Fuel Delivery Temperature



- In addition to the hot and cold case boundary conditions, the fuel delivery temperature also is used to determine the Pressure Ramp Rate and End-of-Fill Pressure Target

Overview – Pressure Ramp Rate (PRR) Control Pressure

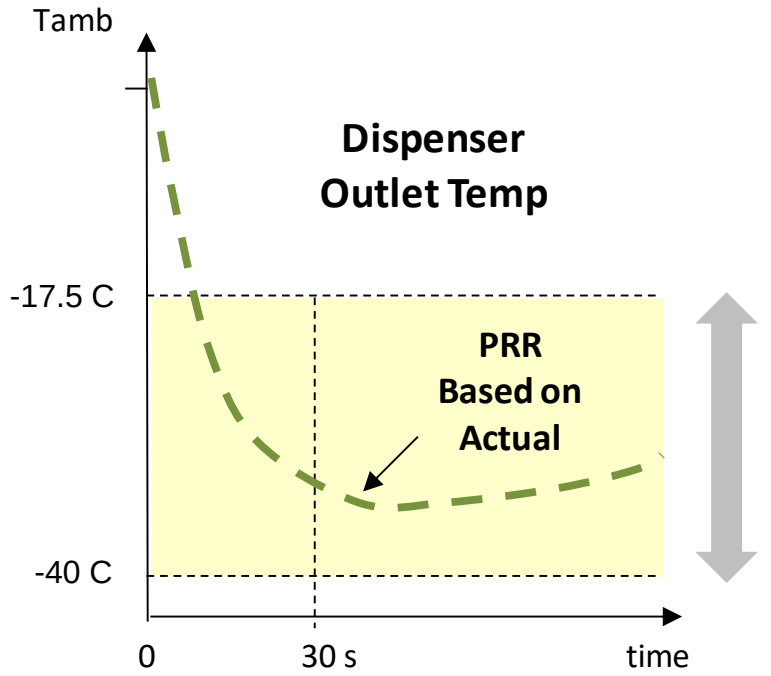
Table Based Protocol



Fuel Delivery Temperature Categories T40, T30, T20

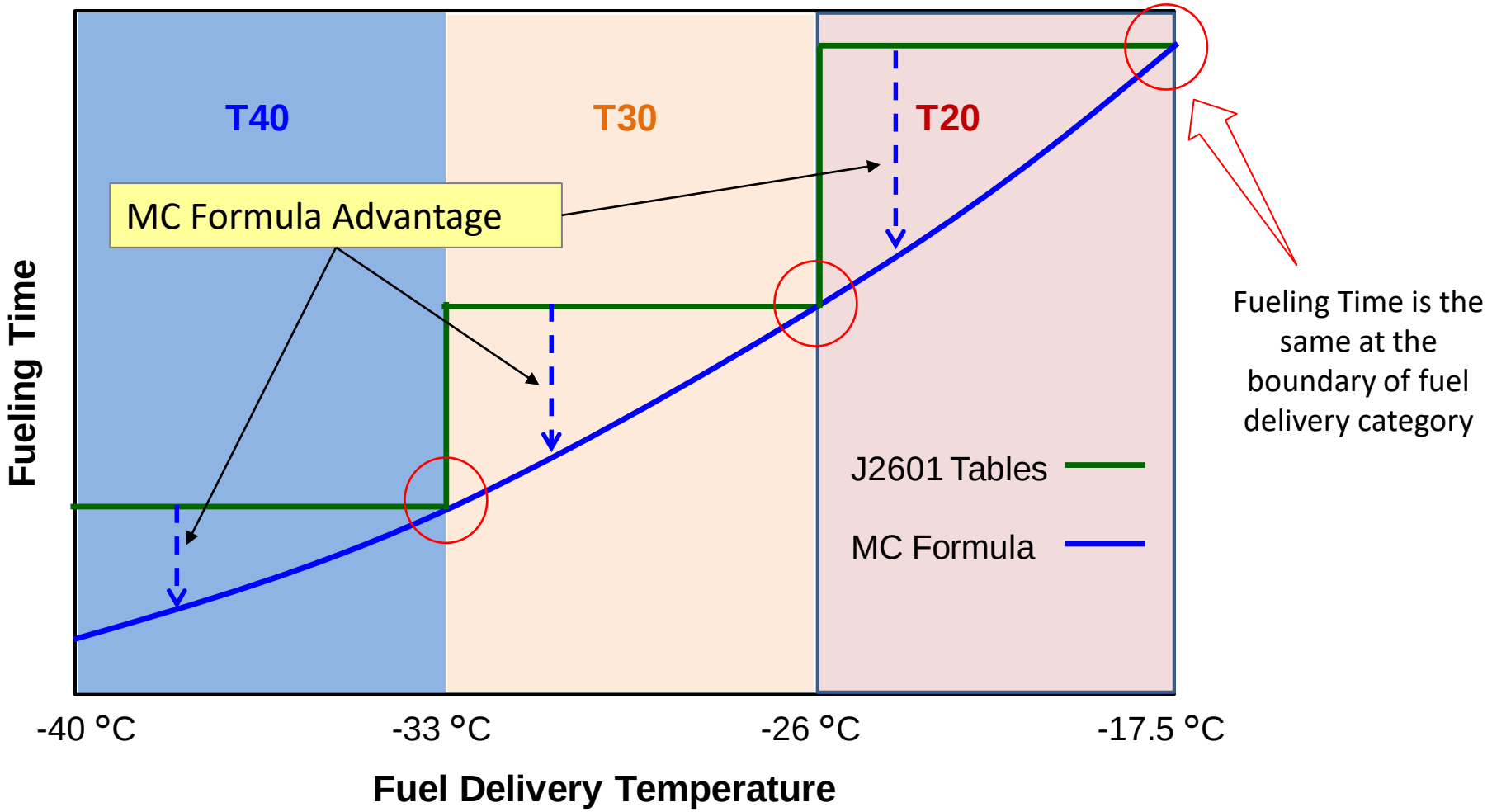
PRR Based on Warmest Temp (upper boundary)

MC Formula Protocol



- Table Protocol uses fuel delivery temperature categories, i.e. T40 must keep -40 °C ≤ Tfuel ≤ -33 °C
- The upper boundary of these categories is used to determine PRR
- MC Formula protocol allows any fuel delivery temperature between -40 °C ≤ Tfuel ≤ -17.5 °C

Overview – Pressure Ramp Rate (PRR) Control Pressure



- MC Formula protocol reduces fill time because it is directly a function of fuel delivery temperature
- J2601 Table protocol fill time is a function of upper boundary of the fuel delivery category (e.g. T40)

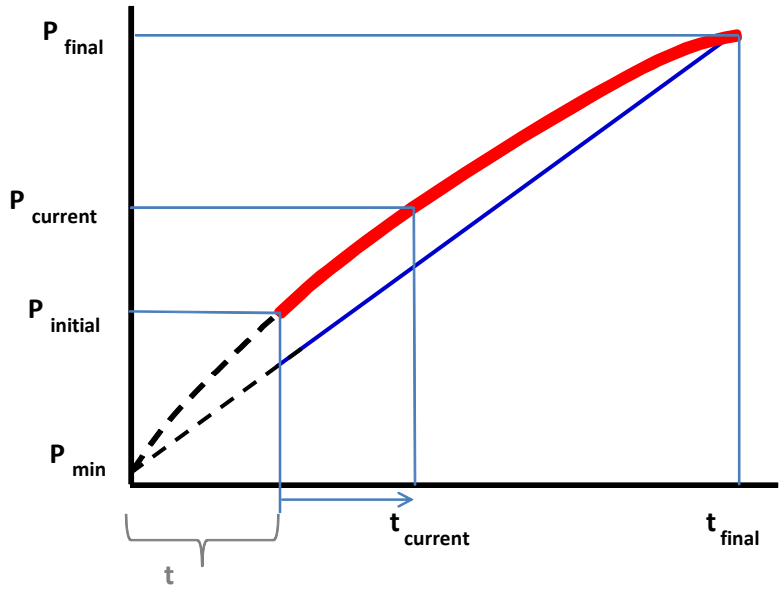
Overview – Pressure Ramp Rate (PRR) Control Pressure

Table Based Protocol

Fuel Delivery Temp input is constant (boundary)
Therefore, PRR is constant

Constant Pressure Ramp Rate (PRR)

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



MC Formula Protocol

Fuel Delivery Temp input is variable (actual)
Therefore, PRR is variable

Variable Pressure Ramp Rate (PRR)

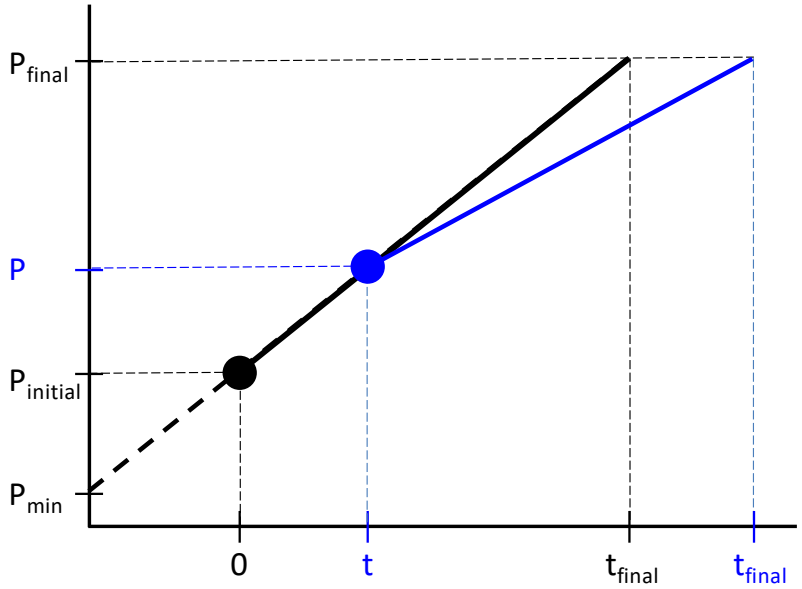
$$PRR = \frac{P_{final} - P_{current}}{t_{final} \times \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{\min}}\right) - t_{current}}$$

- PRR is a function of **t-final** → **t-final** = time required to fill from P_{min} to P_{final} under hot case

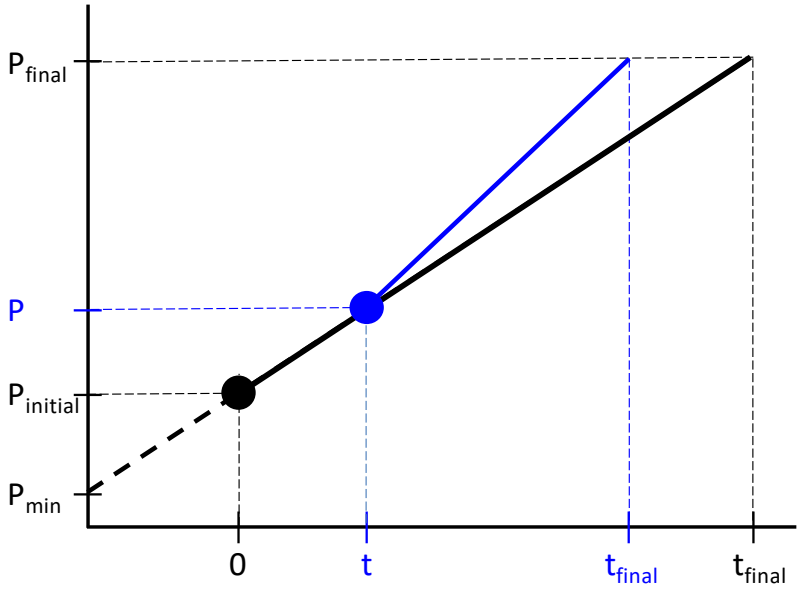
Overview – Pressure Ramp Rate (PRR) Control Pressure

Variable Ramp Rate Control

t_{final} increasing



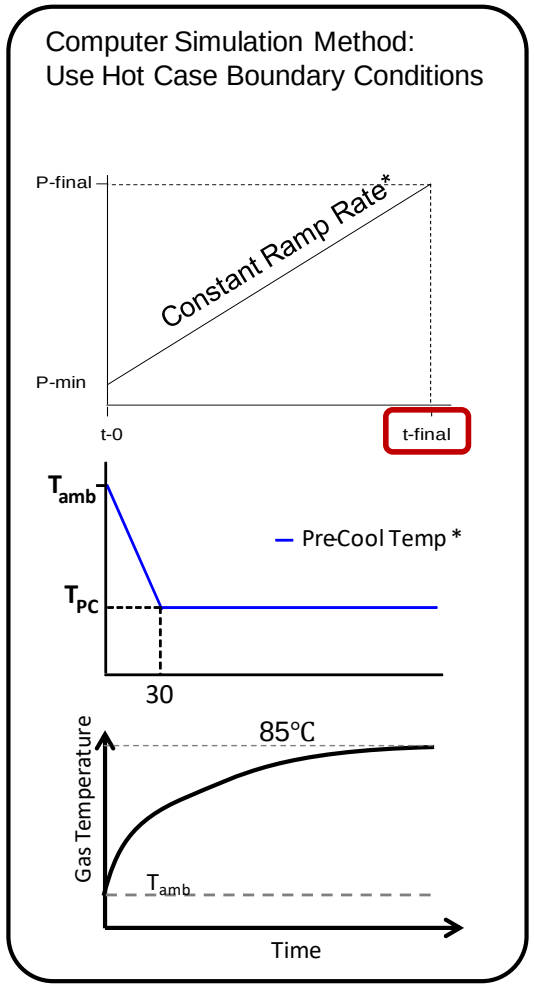
t_{final} decreasing



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

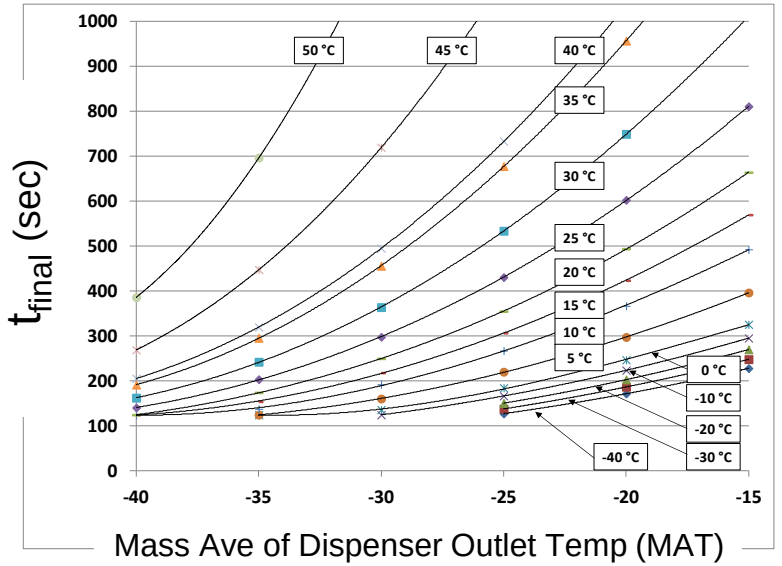
- PRR equation determines the rate of change of station pressure such that P_{final} is reached at time t_{final}
- PRR is calculated & updated every second

Overview – Derivation of t_{final}



- 6 fuel delivery temperatures
- 15 ambient temperatures
- 2 initial pressures
- 4 vessel sizes

720 Total Simulations



- Result is a continuous equation for each ambient temperature
- R2 = 0.999

MAT = Mass Average of Dispenser Outlet Temperature

$$t_{final\,(Tamb)} = a_{(Tamb)} \times MAT^3 + b_{(Tamb)} \times MAT^2 + c_{(Tamb)} \times MAT + d_{(Tamb)}$$

- Computer Simulations conducted to calculate time required (t_{final}) under HOT CASE Conditions
- A cubic polynomial regression fit of tfinal vs MAT is utilized → R^2 = 0.999

Overview – Calculation of t_{final}

$$t_{final\,(Tamb)} = a_{(Tamb)} \times MATC^3 + b_{(Tamb)} \times MATC^2 + c_{(Tamb)} \times MATC + d_{(Tamb)}$$

Where MATC represents the "mass average dispenser outlet temperature" used as the control input

T-amb	a	b	c	d
50	4.514388462E-01	-3.145142974E+02	7.306695058E+04	-5.659824740E+06
45	7.049933102E-02	-4.821054939E+01	1.102055079E+04	-8.419924911E+05
40	1.362862549E-02	-8.260815544E+00	1.651200338E+03	-1.084379676E+05
35	4.592256382E-03	-1.807162289E+00	1.120637098E+02	1.411203687E+04
30	4.285982632E-05	1.144067798E+00	-5.267907363E+02	6.026791301E+04
25	2.355885523E-04	7.644968907E-01	-3.838726125E+02	4.511675817E+04
20	2.020835458E-03	-7.232242970E-01	1.741969529E+01	9.783347285E+03
15	3.495653749E-03	-1.986079447E+00	3.646860190E+02	-2.124398236E+04
10	2.325930317E-03	-1.126206134E+00	1.528858512E+02	-3.779522713E+03
5	3.254083778E-03	-1.837957932E+00	3.334329553E+02	-1.895330972E+04
0	4.243090406E-03	-2.780202650E+00	6.113483920E+02	-4.509030496E+04
-10	5.895584098E-03	-4.046795945E+00	9.333096162E+02	-7.226120299E+04
-20	4.886261021E-03	-3.307007199E+00	7.515142270E+02	-5.729865936E+04
-30	5.968674400E-03	-4.154120397E+00	9.708272308E+02	-7.611219657E+04
-40	3.637633333E-03	-2.431360685E+00	5.455303837E+02	-4.105428816E+04

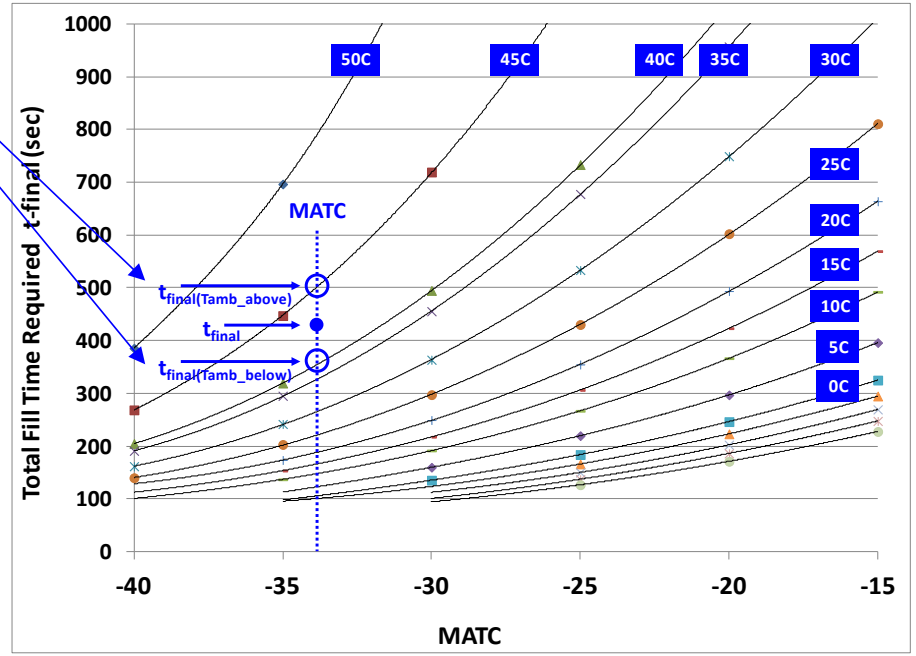


Table of coefficients a, b, c and d

One table for each tank size (2, 4, 7, and 10 kg)

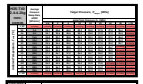
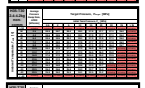
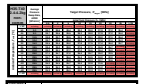
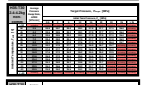
- Interpolation is used to calculate t-final for the ambient temperature
- For a given CHSS volume category, t-final is calculated for the upper and lower boundary tanks and the most conservative value is used.

- The t_{final} value used in the pressure ramp rate equation is determined by the t_{final} equation and interpolation on T_{amb}

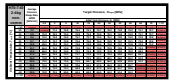
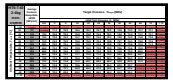
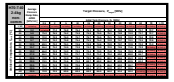
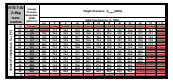
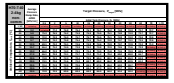
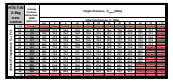
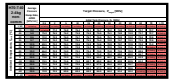
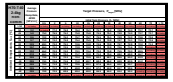
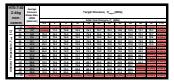
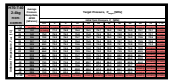
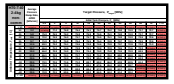
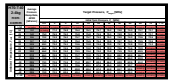
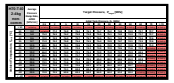
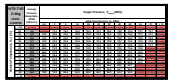
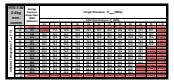
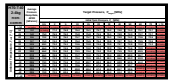
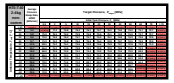
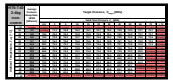
Overview – Structure of t_{final} Coefficient Tables

J2601 Lookup Tables

H35

CHSS Volume	Station Type	Non-Comm	Comm
2.4 to 4.2kg	T40		
	T30		
	T20		
4.2 to 6.0kg	T40		
	T30		
	T20		

H70

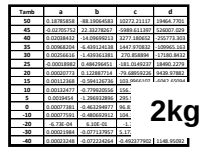
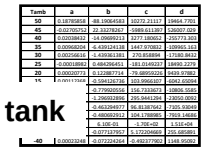
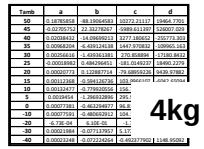
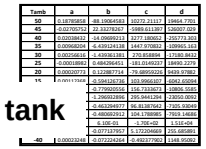
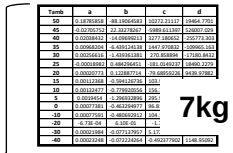
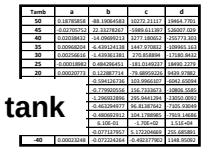
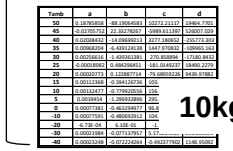
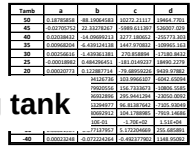
CHSS Volume	Station Type	Non-Comm	Comm
2 to 4kg	T40		
	T30		
	T20		
4 to 7kg	T40		
	T30		
	T20		
7 to 10kg	T40		
	T30		
	T20		

30 Tables

MC Formula

H35 & H70

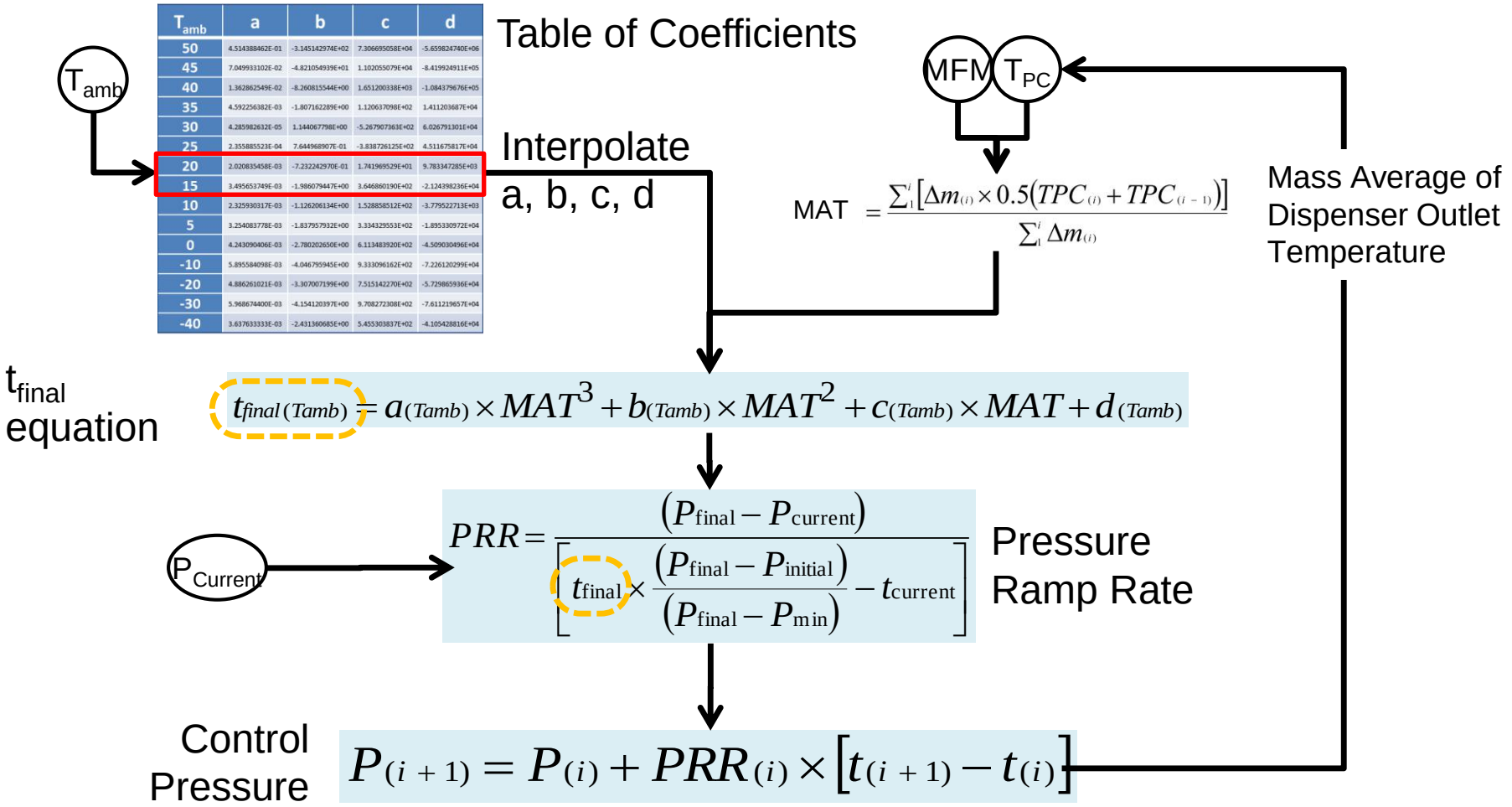
CHSS Volume

CHSS Volume	P_0 < 5MPa	P_0 ≥ 5MPa
2 to 4kg	 2kg tank	
4 to 7kg	 4kg tank	
7 to 10kg	 7kg tank	
	 10kg tank	

8 Tables

- MC Formula uses 8 coefficient tables versus 30 tables for the Lookup Table Method

Overview – How t_{final} is used



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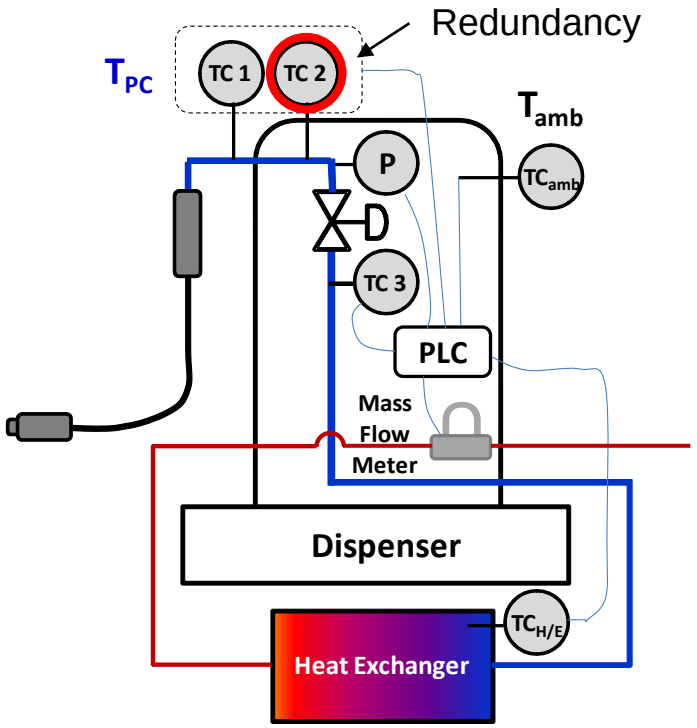
45	7.049933102E-02	-4.821054939E+01	1.102055079E+04	-8.419924911E+05
40	1.362862549E-02	-8.260815544E+00	1.651200338E+03	-1.084379676E+05
35	4.592256382E-03	-1.807162289E+00	1.120637098E+02	1.411203687E+04
30	4.285982632E-05	1.144067798E+00	-5.267907363E+02	6.026791301E+04
25	2.355885523E-04	7.644968907E-01	-3.838726125E+02	4.511675817E+04
20	2.020835458E-03	-7.232242970E-01	1.741969529E+01	9.783347285E+03
15	3.495653749E-03	-1.986079447E+00	3.646860190E+02	-2.124398236E+04
10	2.325930317E-03	-1.126206134E+00	1.528858512E+02	-3.779522713E+03
5	3.254083778E-03	-1.837957932E+00	3.334329553E+02	-1.895330972E+04
0	4.243090406E-03	-2.780202650E+00	6.113483920E+02	-4.509030496E+04
-10	5.895584098E-03	-4.046795945E+00	9.333096162E+02	-7.226120299E+04
-20	4.886261021E-03	-3.307007199E+00	7.515142270E+02	-5.729865936E+04
-30	5.968674400E-03	-4.154120397E+00	9.708272308E+02	-7.611219657E+04
-40	3.637633333E-03	-2.431360685E+00	5.455303837E+02	-4.105428816E+04

- t_{final} equation coefficients a, b, c, and d are chosen from table and then interpolated on ambient temp
- MAT is calculated continuously and input to t_{final} equation to calculate t_{final}
- PRR and Control Pressure is calculated as a function of t_{final} and current pressure $P_{current}$

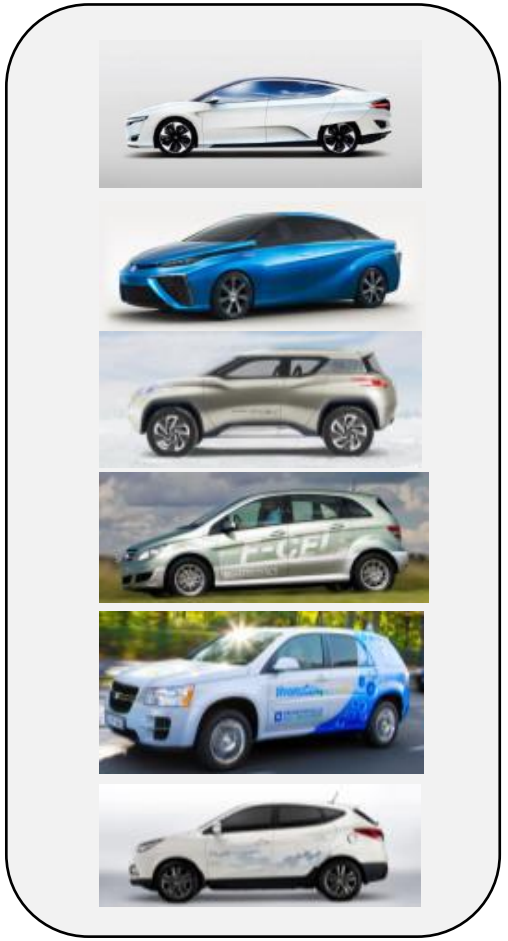
Overview – Requirements

Station Requirements:



Because the fuel delivery temperature is directly used to calculate the pressure ramp rate, it should have a high reliability, i.e. redundant sensors.

Vehicle Requirements:



Same as Table-based (no additional requirements for MC Formula)

- Redundance should be used for the fuel delivery temperature measurement – vehicle requirements are same as table-based

Acknowledgement and Contact

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Notice: