2015 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Analysis of Incremental Fueling Pressure Cost

Amgad Elgowainy (PI) and Krishna Reddi - Argonne National Laboratory

Argonne NATIONAL LABORATORY

June 11, 2015

SA045

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

Overview

Timeline

- Start: October 2013
- End: Determined by DOE
- % complete (FY15): 70%

Barriers/Challenges

- Lack of hydrogen infrastructure options analysis
- Cost and efficiency of delivery components
- Lack of appropriate models and analytical capability
- Conduct unplanned studies and analyses

Budget

- FY14 Funding: $150K
- Total FY15 Funding: $150K
- 100% DOE funding

Partners/Collaborations

- Pacific Northwest National Lab
- Boyd H2
- Honda R&D Americas
- Industry stakeholders

Relevance/Impact

- ❑ Provide a platform for comparing impact of alternative refueling methods and fueling pressures on the cost of dispensed hydrogen
  - ✓ Evaluate impact of fueling pressure on fill rate and refueling cost
  - ✓ Incorporate implications of SAE J2601 and MC Default fill refueling protocols in the modeling of hydrogen refueling stations (HRS)
  - ✓ Identify cost drivers of various fueling technologies and configurations
  - ✓ Evaluate the potential of new concepts to reduce refueling cost
- ❑ Assist in FCTO planning
  - ✓ Investigate delivery and refueling options with potential to achieve cost goals in MYRD&D
  - ✓ Assist with defining R&D areas for future funding priorities to achieve performance targets and cost goals
- ❑ Support existing DOE-sponsored tools (e.g., HDSAM, HRSAM, H2A, GREET and MSM)
  - ✓ Collaborate with model developers and lab partners
  - ✓ Collaborate with industry for input and review

Modeling impact of incremental fueling pressure on refueling cost – Approach

DOE's Fuel Cell Technologies Office (FCTO), Program Plan and Multi-Year RD&D Plan

Analysis Framework

Station performance and cost analysis

Models & Tools

H2SCOPE, HRSAM

H2A models, MSM, GREET, others

Studies & Analysis

Evaluate impact of fueling pressure on refueling rate and cost, and incorporate implications of SAE J2601 refueling protocol and MC default fill method

Outputs & Deliverables

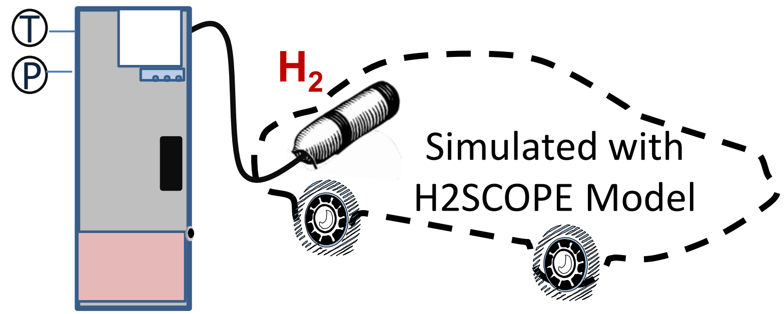
Identify cost drivers of various fueling technologies and configurations and evaluate new concepts to reduce refueling cost

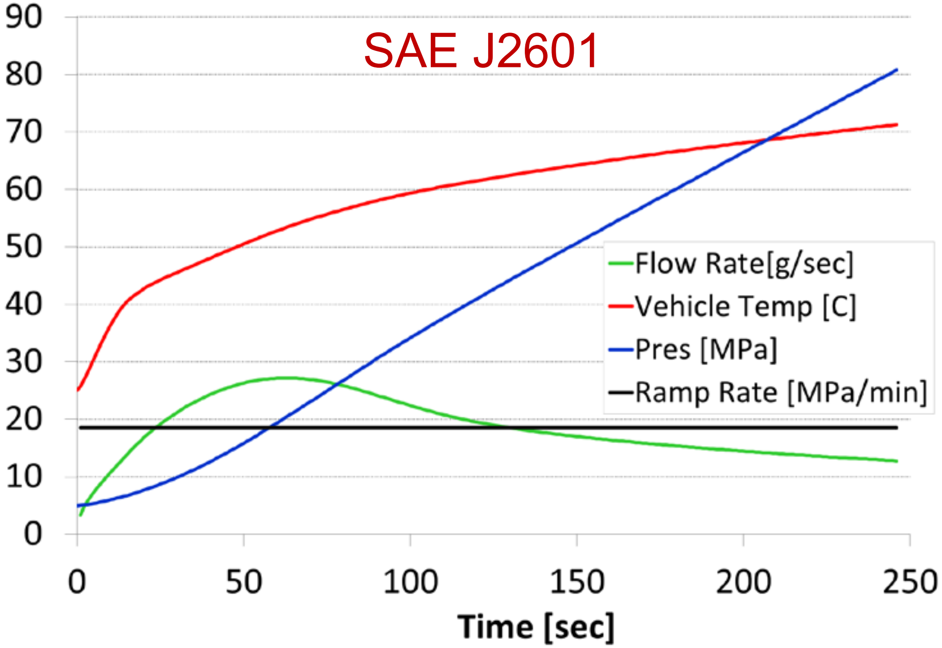
Analytical modeling combined with verification – Approach

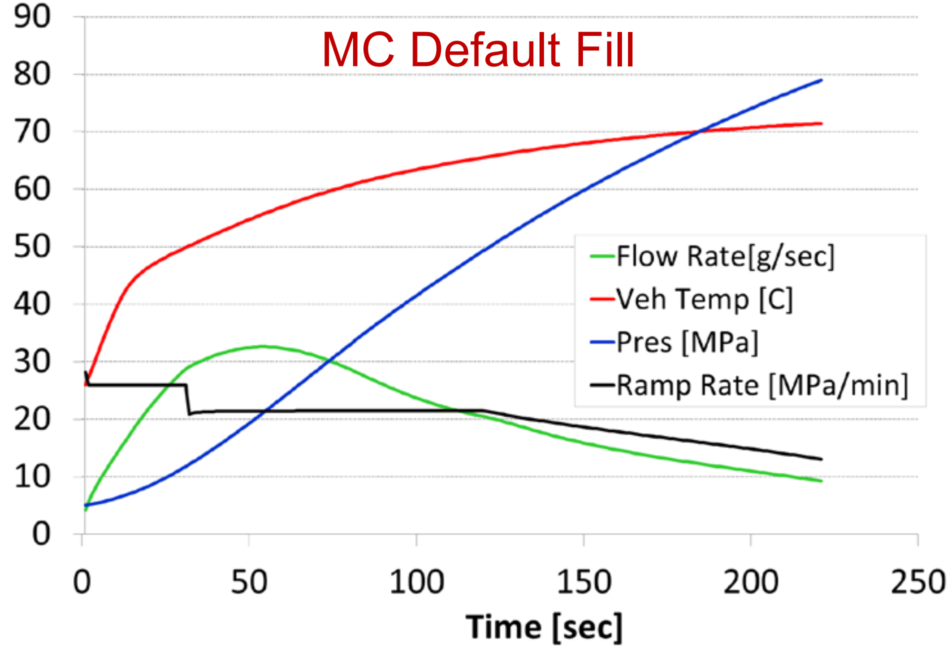
- Develop modeling structure to **optimize** refueling systems
- **Collaborate** to acquire/review model inputs, analyze refueling options, and examine/review results
- **Simulate** performance of refueling system by solving physical laws (i.e., mass, momentum, and energy conservation) and implementing appropriate initial and boundary conditions
- **Examine** pros and cons of existing and new refueling options
- **Identify** major cost drivers for hydrogen fueling
  - Impact of SAE J2601 30-sec window on fill time (vs. MC Default fill method), especially for HRS in early FCEV markets
- **Vet** analysis results and findings
  - Internally via partners
  - Externally, via collaborators and through interacting with US DRIVE Tech Teams and experts from industry

H2SCOPE tracks mass, temperature, and pressure between refueling components and vehicle's tank – Approach

- Solve physical laws (conservation of mass, momentum and energy)
- Simulate various refueling methods (e.g., SAE J2601, MC Default Fill)







MC Default fill dynamically adjusts to the instantaneous precooling temperature at the dispenser

Evaluate various fueling pressures: 350, 500 and 700 bar – Approach

I. Determine precooling requirement for various fill rates and HRS capacities

- Key issues on the vehicle side
  - Tank characteristics:
    - Type IV
    - Tank configuration (number, diameter, length, thickness)
    - Thermal properties (thermal conductivity, specific heat, density)
  - Boundary conditions:
    - Ambient (and pre-soaking) temperature
    - Convective heat transfer (H.T. coefficient)
    - Inlet temperature and flow rate (interface with supply side)
    - Maximum mass, pressure and temperature at end of fill
- Estimate temperature gain between dispenser and vehicle tank

II. Determine refueling cost contribution to $/kg$_{H2}$

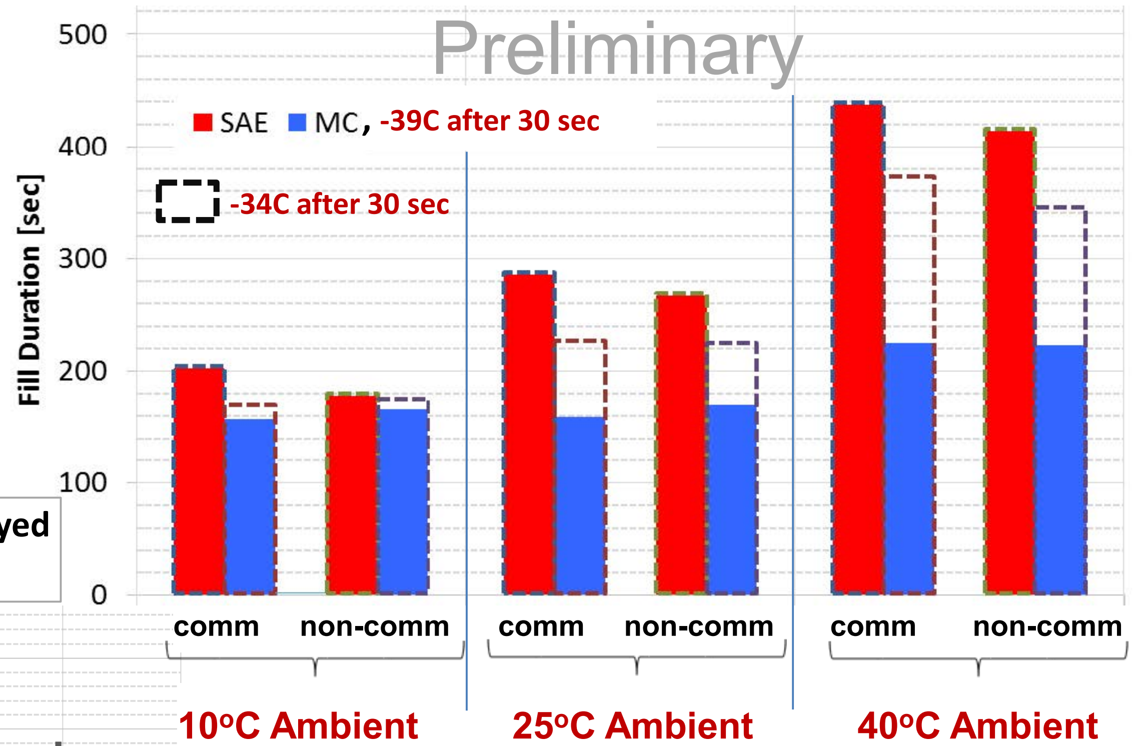
- Key issues on the fueling (supply) side
  - Precooling capacity and cost
  - Cost of storage, compression, and dispensing

7

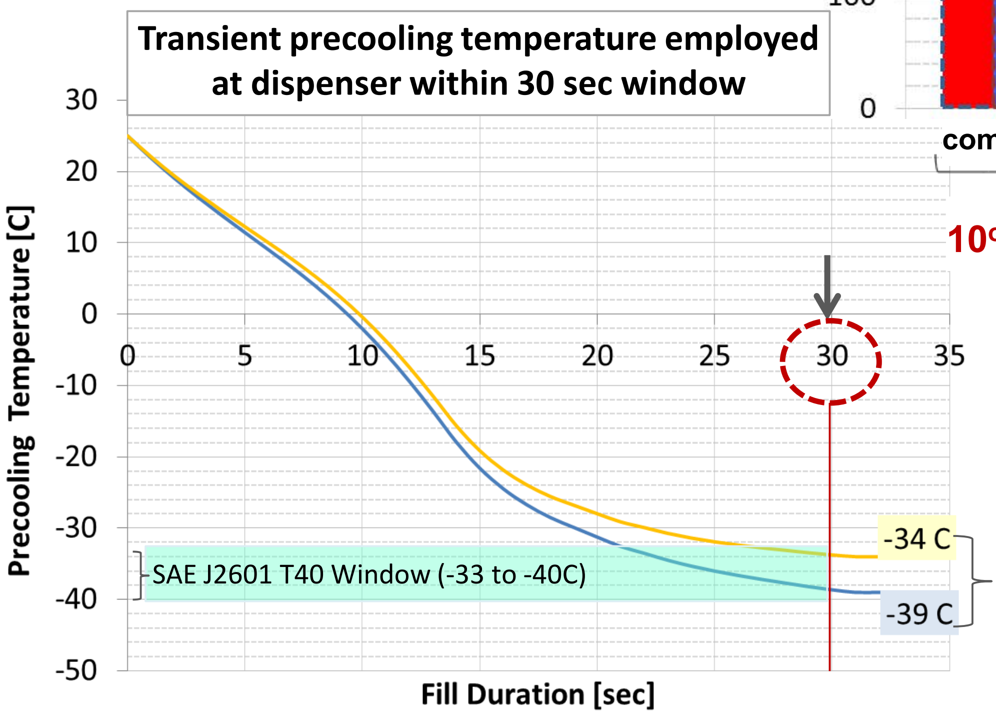
Impact of fueling parameters on fill duration with SAE J2601 and MC Default fill

Fill speed of MC default fill relative to SAE J2601 is a strong function of the actual precooling temperature at dispenser – Accomplishment

The impact of precooling temperature on relative fill speed is more pronounced at high ambient temperatures

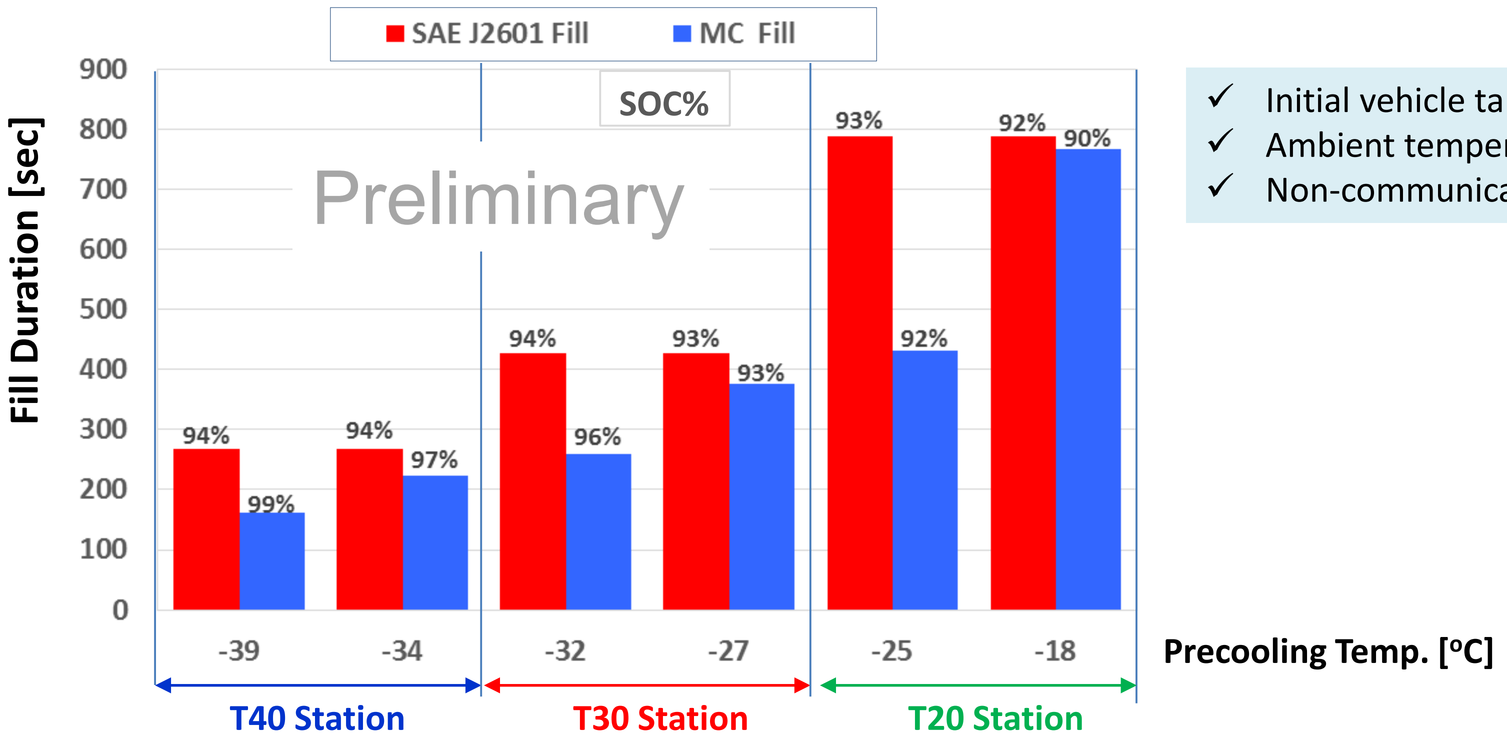


Initial vehicle tank pressure = 5 MPa



Precooling temperature stays constant for the rest of the fill

MC Default fills faster than SAE J2601 fills, particularly at lower precooling temperatures in any temperature window – Accomplishment



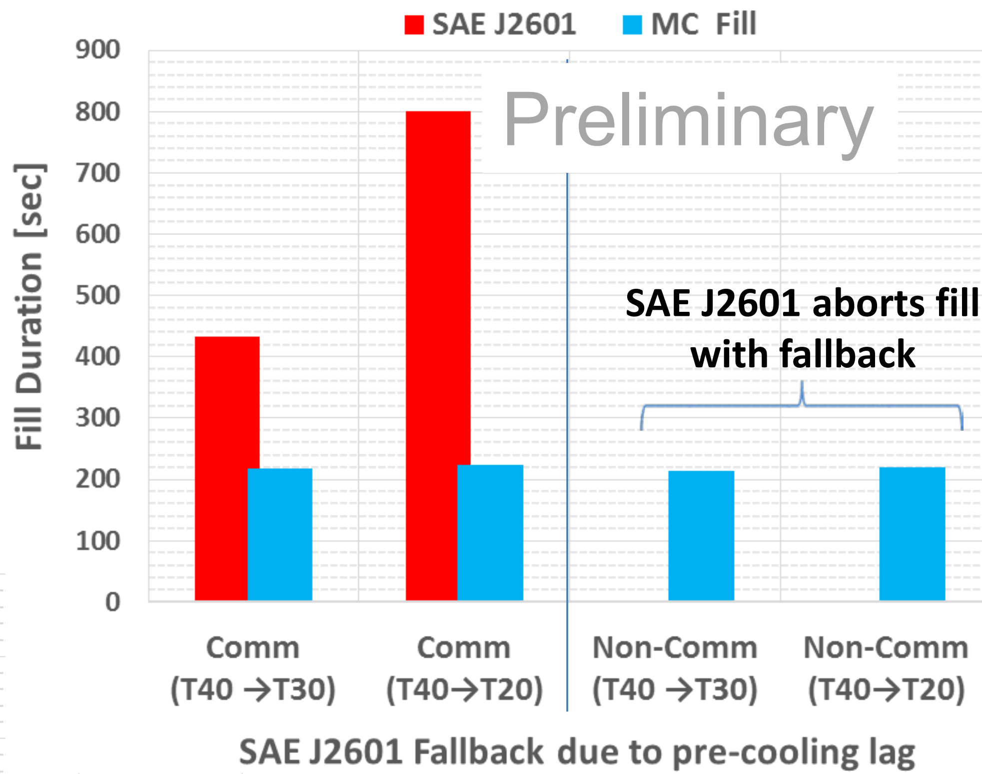
- ✓ Initial vehicle tank pressure = 5 [MPa]
- ✓ Ambient temperature = 25 [°C]
- ✓ Non-communication fill

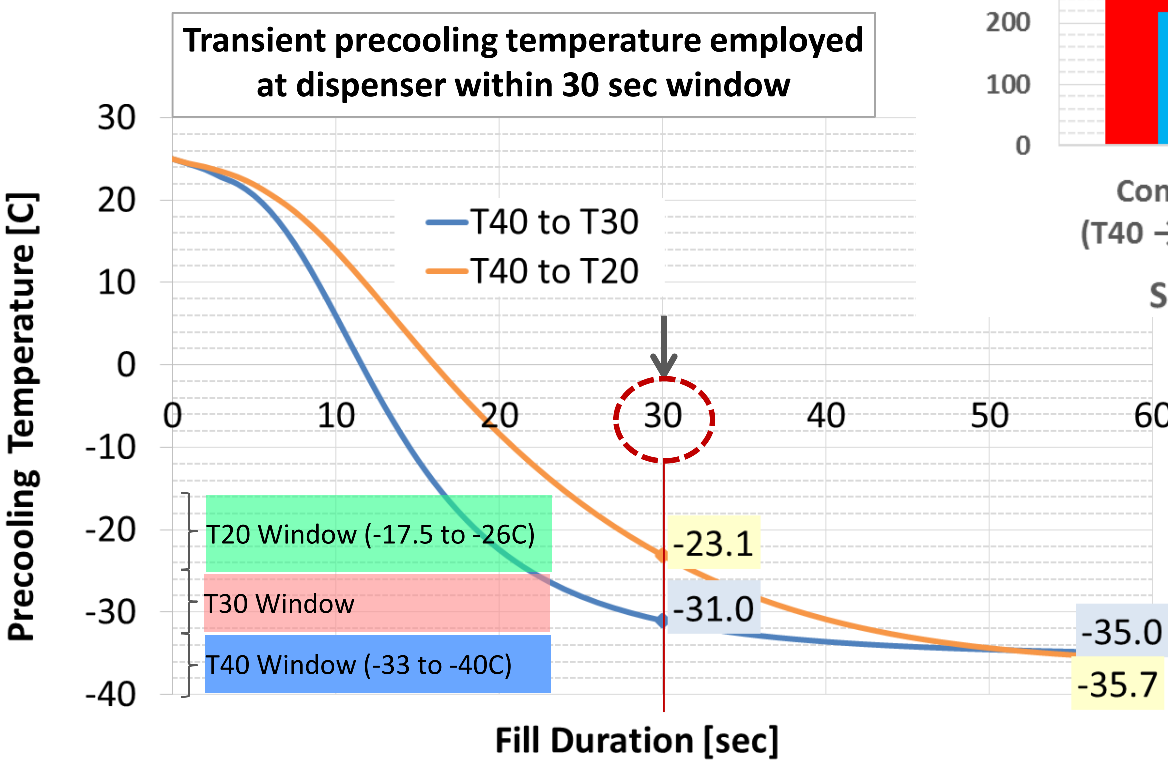
The dynamic adjustment of fill rate with precooling temperature is an advantage provided by MC fills, especially for T30 and T20 stations

Impact of SAE J2601 fallback (due to pre-cooling lag) on the fill duration can be dramatic – Accomplishment

The MC Default method can mitigate the impact of transient cooling lag on the speed of fills, and enable fills that would otherwise be halted (for non-communicating fills)

- ✓ Value to customer satisfaction needs to be evaluated

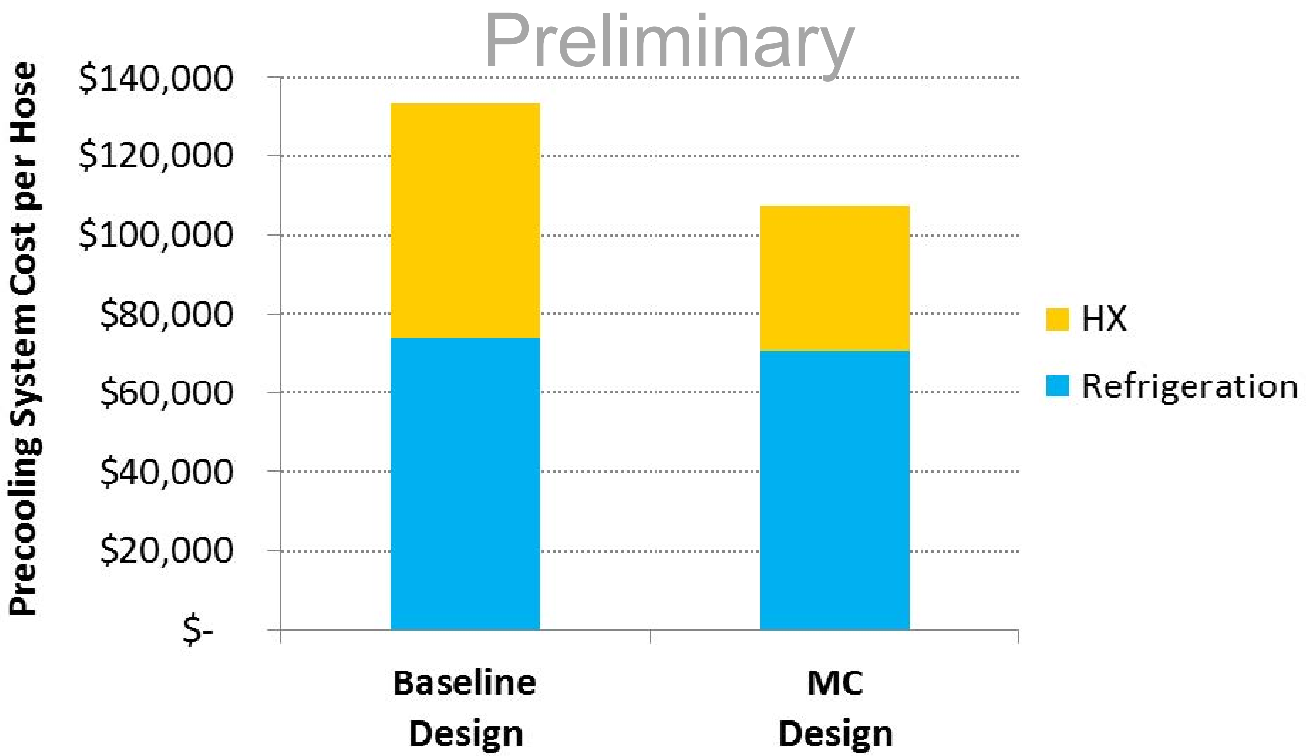




- ✓ Initial vehicle tank pressure = 5 [MPa]
- ✓ Ambient temperature = 25 [^oC]
- ✓ One fallback is allowed

Precooling temperature stays constant for the rest of the fill

MC method can relax precooling design constraints with respect to refrigeration capacity and HX thermal mass – Accomplishment

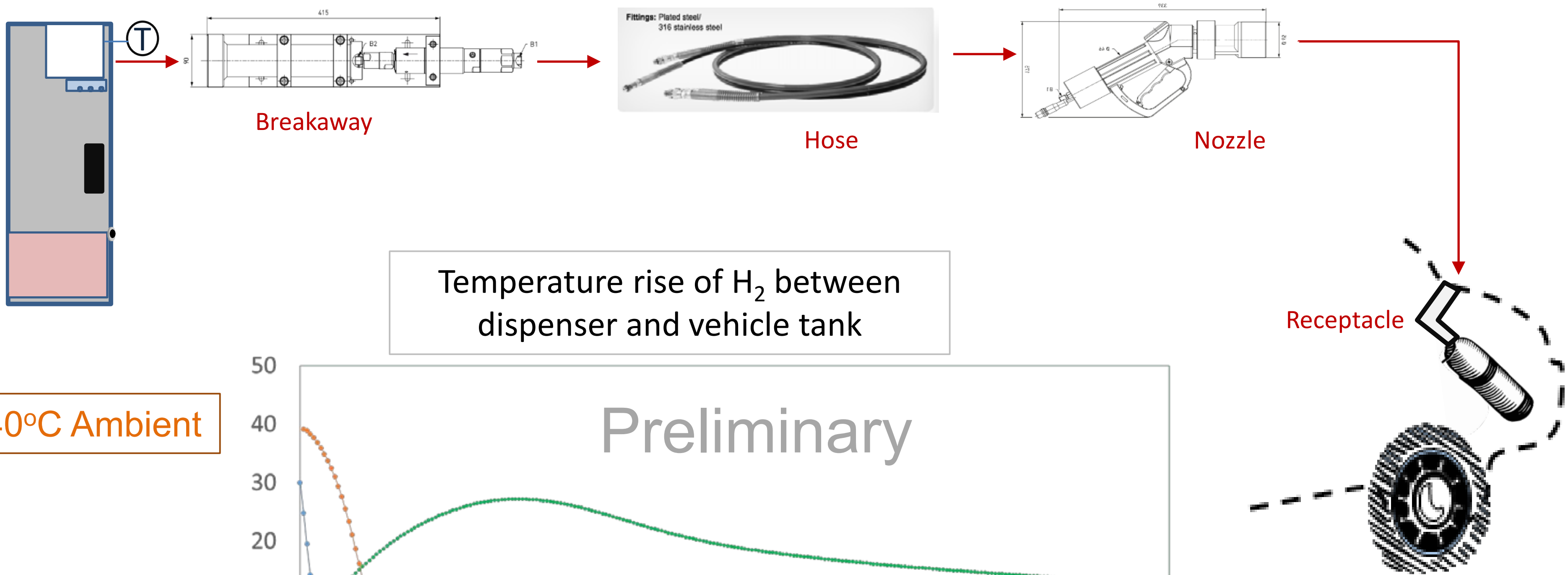


- ~$25,000 (20%) potential cost reduction of precooling system per hose with minimum impact on speed of fills.
  - ✓ Implied cost of customer satisfaction with non-communication fills is additional

Impact of fueling pressure
(700, 500 and 350 bar)
on fill duration and cost

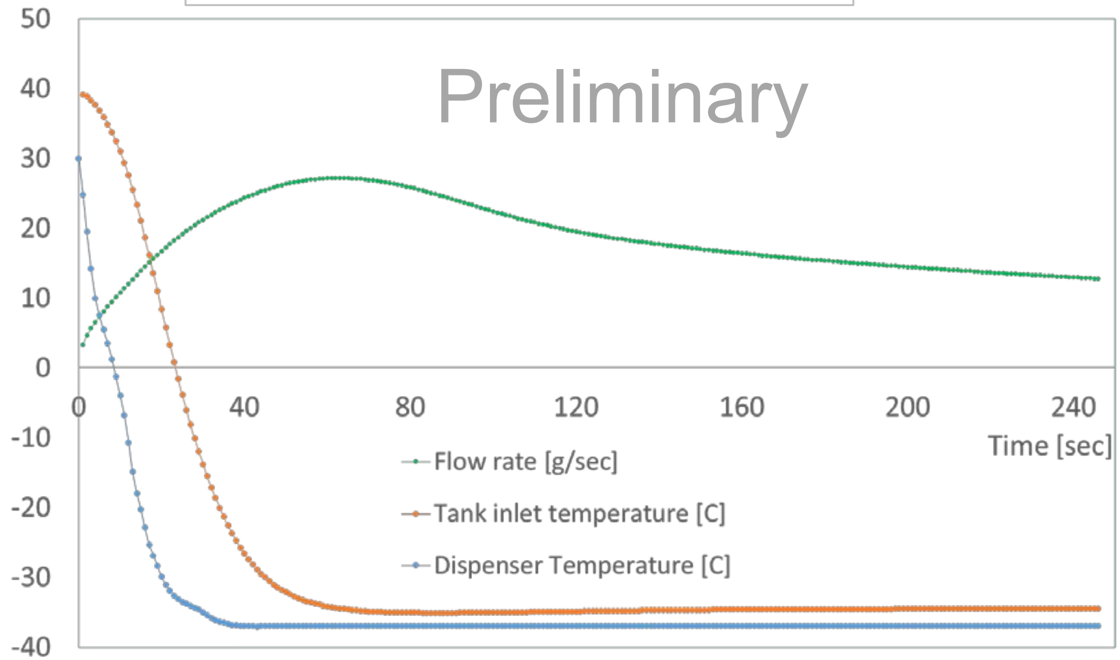
(Parametric Analysis)

Modeled temperature rise between the dispenser and vehicle tank – Approach



40°C Ambient

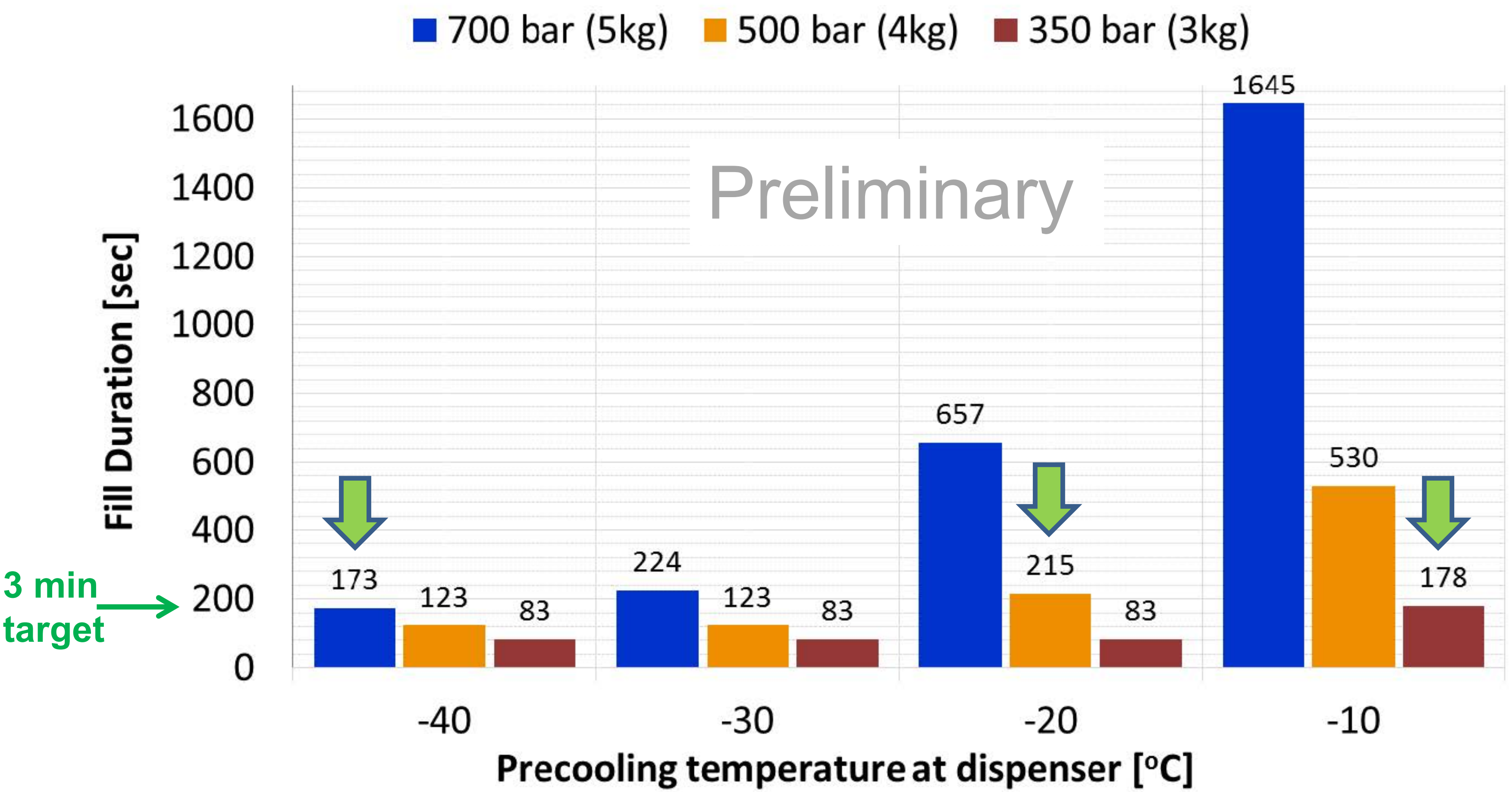
Temperature rise of H_2 between dispenser and vehicle tank



✓ H_2 temperature rise between dispenser and vehicle tank needs to be verified

Fueling pressure impacts fill duration at elevated precooling temperature – Accomplishment

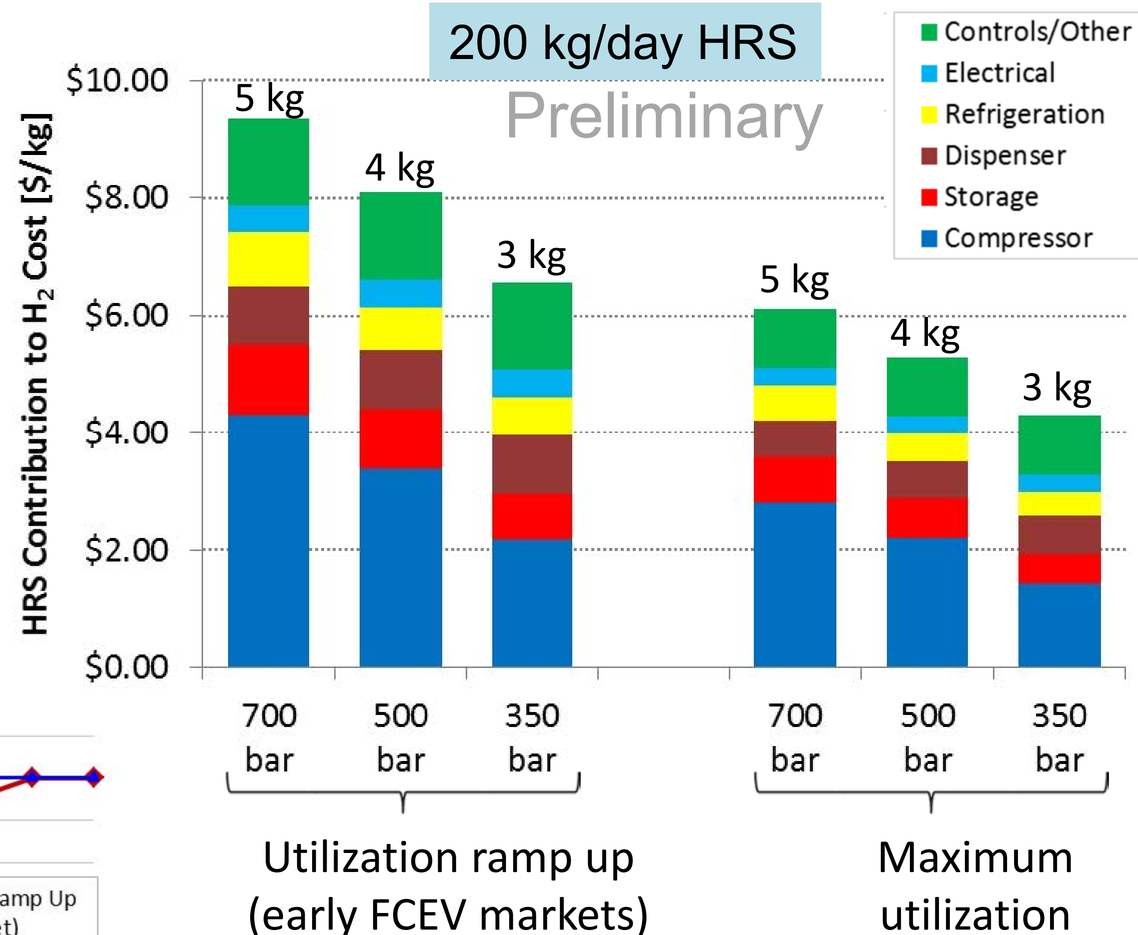
- ❖ Same 700 bar tank for all dispensing pressures
- ❖ 40°C Ambient (no pre-soak)

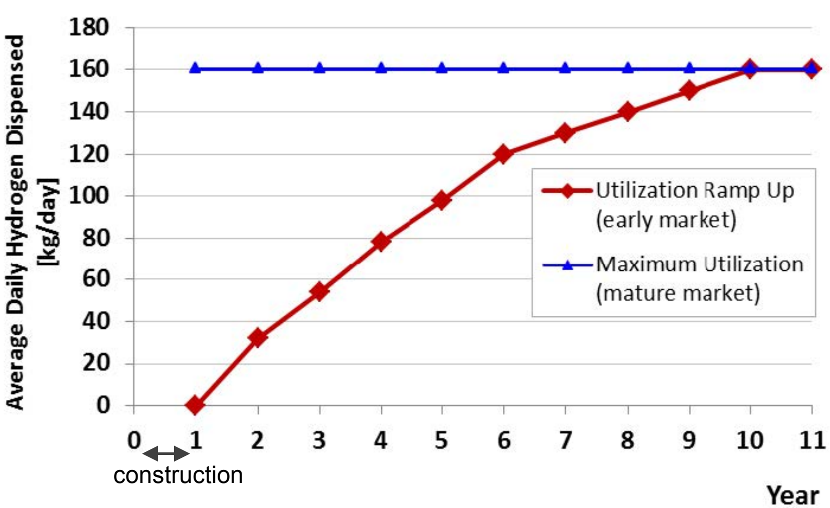


- ➢ Less precooling is needed for partial fills
  - ✓ Implication of partial fills on customer satisfaction needs to be evaluated

Partial vehicle fills (with lower fueling pressures) reduces refueling cost – Accomplishment

The contribution of HRS to H_2 cost can be reduced by up to \$3/kg with partial fills in early FCEV markets





✓ Implication of partial fills on customer satisfaction needs to be evaluated

Summary – Progress and Accomplishment

- Updated the H2SCOPE model with the final release of SAE J2601 and incorporated the MC Default fill method to evaluate various fueling methods, precooling temperatures and fueling pressures
- The dynamic adjustment of the MC Default fill flow rates with precooling temperature provided faster fills
  - ✓ With the opportunity to reduce precooling system cost by 20%
- Less precooling is required for partial fills
  - ✓ The contribution of HRS to H_2 cost can be reduced by up to $3/kg with partial fills in early FCEV markets
  - ✓ Implication on customer satisfaction needs to be evaluated

Collaborations and Acknowledgments

Collaborators and Partners:

– PNNL: Daryl Brown provided cost of refrigeration and heat exchanger equipment

– Boyd Hydrogen: Bob Boyd provided specific data on refueling equipment required for modeling flow and thermal behavior of hydrogen between refueling components

– Honda R&D Americas: Steve Mathison provided input that was critical for the understanding of various fill methods

Future Work

- Verify modeling results against fill speed and precooling temperatures using measured refueling data
- Evaluate trade-off between refueling speed and refueling cost for various precooling system designs and concepts with MC Default fill method
- Update HDSAM and HRSAM models to include MC Default fill as an option to enable evaluation of refueling cost with various fueling protocols
- Document the analysis in peer-reviewed publications and release updated version of the models for use by researchers and stakeholders
- Continue to evaluate the interaction between vehicle storage options/fueling protocols and refueling equipment/cost
- Continue to provide technical support to FCT Office, hydrogen community, and industry stakeholders

Project Summary

- **Relevance:** Evaluate impact of fueling pressure on fill rate and refueling cost. Incorporate implications of SAE J2601 and MC Default fill refueling protocols in the modeling of hydrogen refueling stations. Identify cost drivers of various fueling technologies and configurations.
- **Approach:** Develop modeling structure to optimize refueling systems. Collaborate to acquire/review model inputs, analyze refueling options, and examine/review results. Simulate performance of refueling system by solving physical laws. Examine pros and cons of existing and new refueling options. Identify major cost drivers for hydrogen fueling. Vet analysis results and findings via partners and through interacting with US DRIVE Tech Teams and experts from industry.
- **Collaborations**: Collaborated with experts from the industry with knowledge and experience on fueling equipment, refueling protocols, and vehicle tanks. Acquired information needed for the simulations and received critical input to refine the analysis.
- **Technical accomplishments and progress:**
  - Updated the H2SCOPE model with the final release of SAE J2601 and incorporated the MC Default fill method to evaluate various fueling methods, precooling temperatures and fueling pressures.
  - The dynamic adjustment of the MC Default fill flow rates with precooling temperature provided faster fills with the opportunity to reduce precooling system cost by 20%.
  - The contribution of HRS to H_2 cost can be reduced by up to \$3/kg with partial fills in early FCEV markets, but the implication on customer satisfaction needs to be evaluated.
- **Future Research**: Verify modeling results against measured fill speed and precooling temperatures. Evaluate trade-off between refueling speed and refueling cost for various precooling system designs and concepts using MC Default fill. Update HDSAM and HRSAM models to include MC Default fill as an option to enable evaluation of refueling cost with various fueling protocols.

Argonne NATIONAL LABORATORY

Amgad Elgowainy
aelgowainy@anl.gov
Project SA045

Acronyms

- ANL: Argonne National Laboratory
- APRR: Average Pressure Ramp Rate
- Comm: Communication fills
- DOE: Department of Energy
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- GREET: Greenhouse gas, Regulated Emissions, and Energy in Transportation
- H_2: Hydrogen
- H2A: Hydrogen Analysis
- H2SCOPE: Hydrogen Station Cost Optimization and Performance Evaluation
- HDSAM: Hydrogen Delivery Scenario Analysis Model
- HRSAM: Hydrogen Refueling Station Analysis Model
- HRS: Hydrogen Refueling Station
- H.T.: Heat Transfer
- HX: Heat Exchanger
- MSM: Macro-System Model
- MYRD&D: Multi-Year Research, Development, and Demonstration
- Non-comm: Non-communication fills
- SAE: Society of Automotive Engineers
- SOC: State Of Charge
- Temp: Temperature

Technical Backup Slides

Define vehicle tank characteristics: Dimensions – Approach

- Tank dimensions (single tank):
  - Type IV, 700 bar (5 kg) from GM SAE paper 2011-01-1342, Immel 2011
  - Fueling pressure of 350 and 500 bar in same tank as 700 bar (3 and 4 kg, respectively)

Vehicle Tank			
Fueling Pressure	700 bar	500 bar	350 bar
Capacity	5 kg_{H2}	4 kg_{H2}	3 kg_{H2}
Outer Diameter [inch]	19.5		
Thickness [inch]	1.83		
Tank Length [inch]	49.2		
Liner Thickness [inch]	0.20		
Volume [L]	129		

Define vehicle tank characteristics: Thermal properties – Relevance/Approach

Vehicle Tank		
	Composite	Liner
	Temperature Range (-100°C to 140°C)	Type IV (PE, -100°C to 140°C)
Density [kg/m³]	1550	975
Specific Heat [J/kg-K]	500 – 1500	1000 – 3000
Thermal Conductivity [W/m-K]	0.3 – 0.8	
Thermal Diffusivity [cm²/sec]	0.001 – 0.009	

Transient precooling temperature employed at dispenser within 30-sec window for comparing MC Default fills with SAE J2601 fills