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Fuel Tank Full-Fill Considerations

Natural Gas Vehicle Technology Forum
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Gas Technology Institute

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List of Topics

- Background
  - Defining a full-fill
  - Defining the issues in gaseous fueling
  - Defining the impact
- Discuss temperature compensation
- Discuss barriers/solutions to better dispenser controls – CEC Project
- Discuss additional improvements

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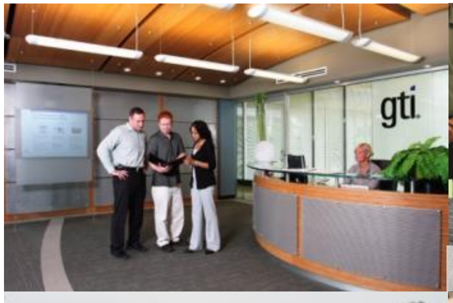
Gas Technology Institute Overview

Natural Gas Research and Development Focus

- > Staff of 300
- > 350 active projects
- > 1,200 patents; 500 products



Training

Office & Labs

Pilot-Scale Gasification Campus

Energy & Environmental Technology Center

Defining a Full-Fill

- Full-fill: 3600 psi (settled P) at 70 °F (settled T)
- Temperature compensation: Correcting for pressure changes due to temp changes in the gas
  - "Full" Density: 1800 psi at -40°F and 4500 psi at 130°F
- Heat of compression: Pressure rise causes temp in cylinder to rise quickly (makes fast-filling difficult)
  - Temporarily high T and P causes fueling procedure to stop with less than "full" density

Defining a Full-Fill

- Dispenser control strategies determine stopping target pressure (typically pressure table based on ambient temp)
- Under many conditions fills do not reach “full” density
  - Sometimes 20% - 30% less than optimal
- Driver’s perception of “full” is important
  - Pressure is a poor indication of “full”
  - Temperature compensated fuel gauge

Defining the Issues

- High ambient temperatures and amount of gas in cylinder are major contributors to under-filling
  - Though many other factors influence final density
- Industry direction is demanding better solutions
  - Cylinders are larger (>150 GGEs on-board)
  - Fills are getting faster (high flow dispensers)
  - Success of industry leads to higher expectations (OEMs and very large fleets) and higher impacts for safety/reliability/consistency
- Safe fills are essential to industry growth

Defining the Impact

- Significant under-filling affects major issues in the industry:
  - Cost (up to 10% of conversion cost)
  - Range (100's of miles – 30 GGE "missing" on HD trucks with 150 GGE of storage)
  - Weight/Space (critical for important markets)
  - Fuel economy (impacts environmental, cost, and range concerns)
  - Customer Satisfaction – misunderstandings lead to bad experiences and disappointments

Primary Safety Concern: Temperature Compensation

> Temperature Compensation: For a given gas composition, there is a constant density that equals 3600 psi at 70 °F (~0.21 g/cm^3 for typ. NG)

> Safety is primary concern-dispensers use of temperature compensation is important
  - Without compensation a fill can occur at high pressures in very cold conditions resulting in over-filling
  - CVEF white paper defines issue and best practices
  - Accountability and verification is key

> CSA NGV 4.3 – Tasked with addressing this issue
  - Initial topic: Defining settled pressure at various temps

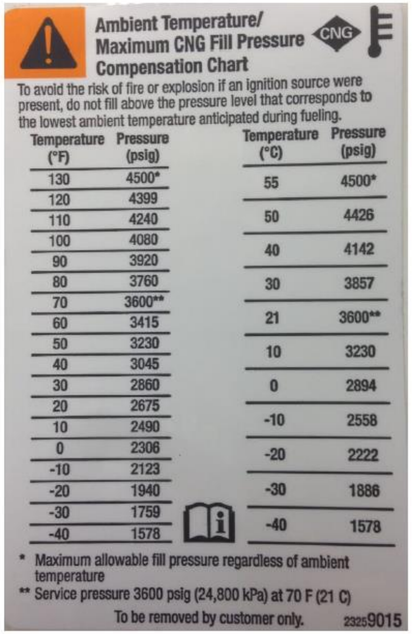
Pressure related to fuel composition

- > Gas composition impacts temp comp. pressure
- > GM chart uses pressure limits for worst case conditions
- > Difficulties on mandating max. settled pressures
- > Temp comp. vehicle gauge could help

Temperature Compensated Fill Chart

Using two “extreme” Natural Gas available/measured compositions – one cleaner (> 97 mol% CH_4) and the other with ~ 75 mol% CH_4

Temperature (°F)	Pressure (psia)	Density (g/cm³)	Temperature (°F)	Pressure (psia)	Density (g/cm³)
130	4558.7	0.197	130	4709.7	0.247
120	4399.4	0.197	120	4525.1	0.247
110	4239.9	0.197	110	4340.4	0.247
100	4080.2	0.197	100	4155.4	0.247
90	3920.2	0.197	90	3970.4	0.247
80	3760.2	0.197	80	3785.3	0.247
70	3600	0.197	70	3600	0.247
60	3439.5	0.197	60	3414.8	0.247
50	3279	0.197	50	3229.6	0.247
40	3118.3	0.197	40	3044.5	0.247
30	2957.6	0.197	30	2859.5	0.247
20	2796.9	0.197	20	2674.8	0.247
10	2636.1	0.197	10	2490.4	0.247
0	2475.3	0.197	0	2306.4	0.247
-10	2314.7	0.197	-10	2122.9	0.247
-20	2154.1	0.197	-20	1940.3	0.247
-30	1993.8	0.197	-30	1758.5	0.247
-40	1833.8	0.197	-40	1577.9	0.247



Conservative approach : maximum allowable fill pressure corresponding to worst case scenario

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GM RESEARCH & DEVELOPMENT

Anne Dailly and Richard Krentz. “Compressed natural gas temperature compensated pressure fill”

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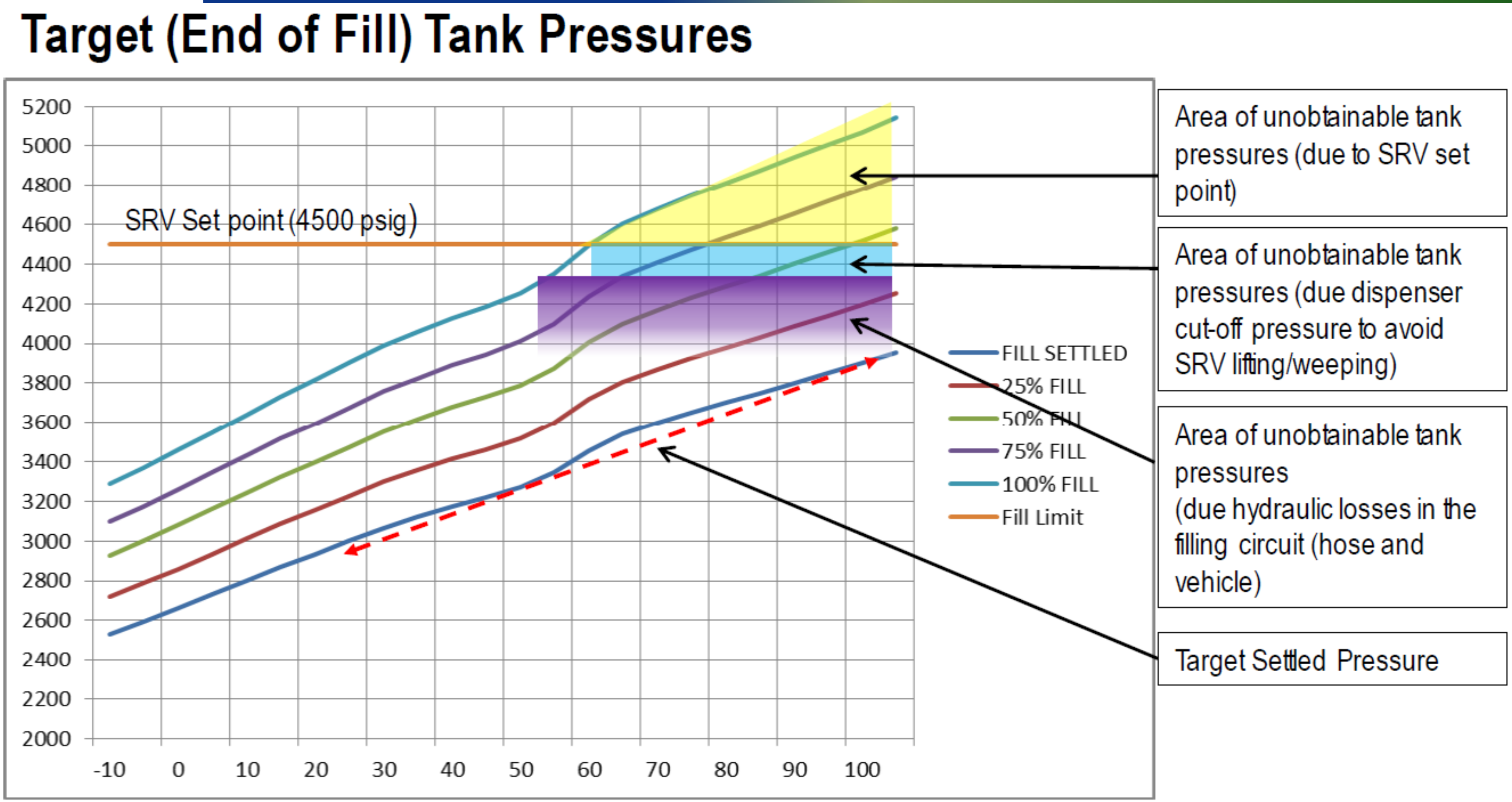
Full-Fills: Optimized Temperature Compensation

- Temperature compensation is also important part of full-fill considerations but only one side of the issue
- Maintaining safe limits for station and vehicle (i.e. preventing over-filling) while optimizing fill (i.e. reducing under-filling) presents significant challenges
- Utilizing "target" stop pressure estimates without accounting for additional factors will not meet goals of safety and customer satisfaction

Full-Fills: System Design Parameters

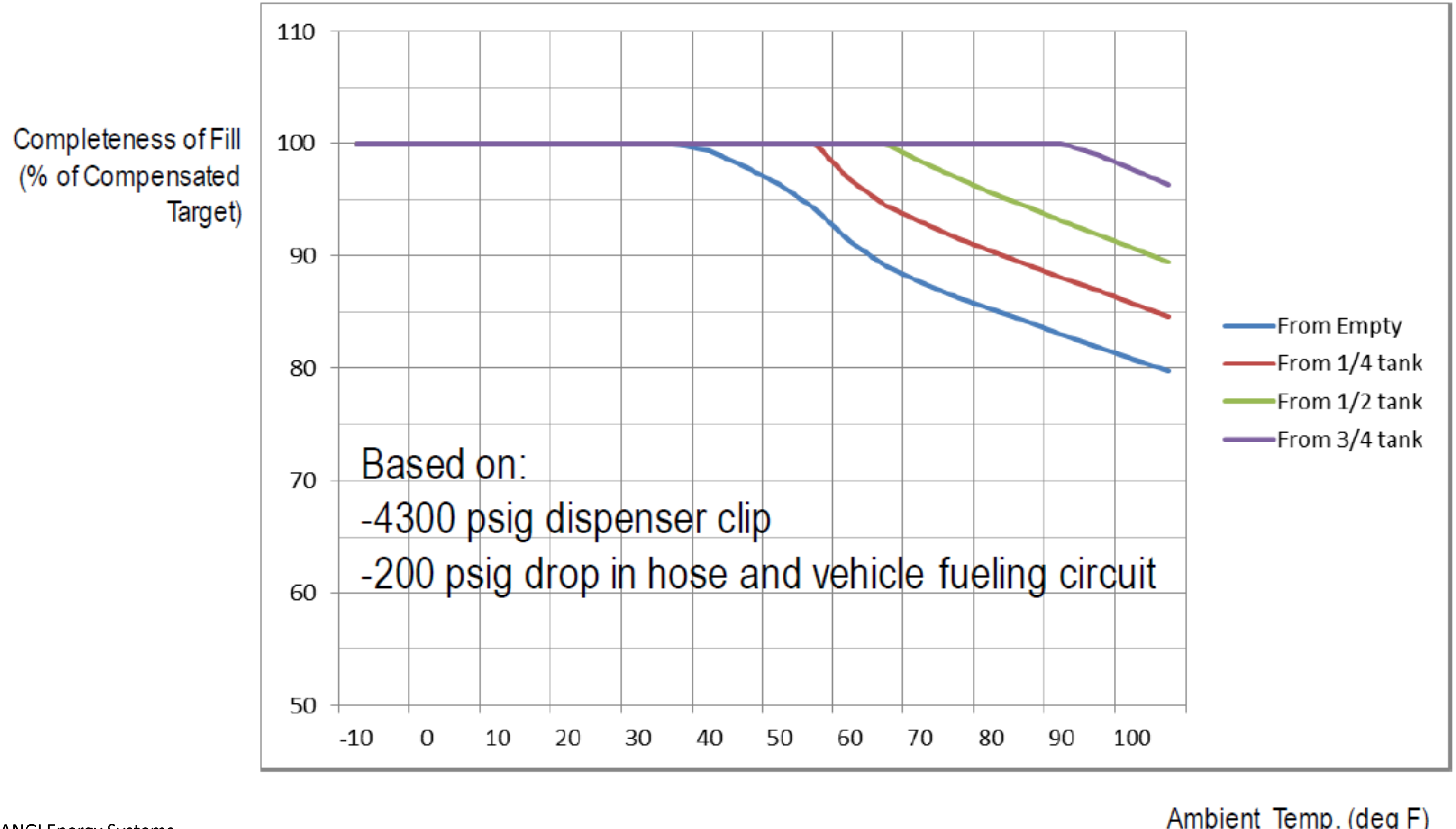
- Safe operation demands code compliance (ANSI NGV2, NFPA 52, others)
- Major design parameters include:
  - Max. settled pressure of 3600 psi at 70 °F
  - Max. over-pressurization limit 125% = 4500 psi
  - Max. temperature of cylinder during fill = 180 F
  - Max. pressure relief in dispenser = 4500 psi (4300 psi, practically)
- Practical operations of station reduce available gas supply

Barrier: Target Stopping Pressure



Barrier: Target Stopping Pressure

Fill Completeness Forecast



Station Control Improvements

- Several “solutions” do exist to improve fueling performance
- First, discuss dispenser controls/algorithms
- CEC funded GTI under PON-14-502 – Infrastructure Improvement Research for Natural Gas Fueling Stations
- Major project partner: ANGI
- Builds on past experience and successes
  - Accufill mass-based fueling protocol

GTI's Current CEC Project

- The goals of the proposed project are:
  - Develop an advanced fueling control method (including initial characterization step)
  - Design a test system that delivers improved fills
  - Validate and quantify benefits
  - Demonstrate improvements in cost-effectiveness and efficiency of fueling infrastructure and vehicle costs
- Looking at the issues that are in station's control (i.e. non-communications)
  - Largest, most immediate impact for existing industry

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GTI's Current CEC Project

- Concern is that dispenser pressure tables alone are trying to solve a complex problem with a simple solution – lead to unacceptable under-filling
- Calculation of internal energy based on variety of variables (known, calculated, and bounded)
- Accurate control requires compensation for:
  - Initial cylinder gas pressure, temperature, composition
  - Initial station gas pressure, temperature, composition
  - Cylinder volume and thermal resistance (varies by type)
  - Flow rate of gas
  - Ambient Temperature

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GTI's Current CEC Project

- Initial modeling has shown important parameters and consistent results with past testing
  - Simulink modeling to calculate internal energy in cylinder
- Limited initial testing of baseline dispensers has shown that 20% under-filling occurs
- Test data from large fleet has shown significant under-filling even when using customer controlled fill settings
- Design of Experiments: evaluate all variables and quantify their importance
- Continued modeling and testing over the next year

Potential “Solutions” (or at least advancements)

- Controls/Algorithm improvements
  - Additional input/data/testing will be needed
  - Potentially leads to standardized control process
- Station equipment improvements – compressor, valve panels, dispensers
  - Improve hydraulic losses/pressure drops and improve flow, redundant pressure transducers to decrease error
- Increase pressure limit on dispenser PRDs
  - PRD setting at ~5000 psi would allow stations to utilize existing gas pressure

Potential "Solutions" (or at least advancements)

> Pre-cooling (i.e. heat exchanger/chiller to lower temperature of supply gas)
  – Done in some situations today; tied to optimized algorithm
  – Disadvantages include capital and operating costs

> Communications (active or passive)
  – Cylinder volume, cylinder type, gas temperature, gas pressure from vehicle to dispenser would provide benefit
  – Disadvantages include existing vehicles, timing, etc.

> Vehicle controlled fueling termination
  – Control valve stops fill based on vehicle pressure and temp
  – Control/liability passes to vehicle

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Potential “Solutions” (or at least advancements)

- Vehicle cylinder type can improve heat removal/loss
  - Type IV cylinder is great insulator
  - All other cylinder types have better thermal properties (i.e. provide heat sink and increased conduction)
  - Unclear how effective heat removal is during fast-fill and doesn’t lead to industry wide solution
- Improve “low-end” pressure limits
  - Minimum fuel rail pressure and supply regulator droop = ~200 – 400 psi (5-10% “stranded” gas)
  - Engine/Injector operability limitations
  - Improved equipment on-board vehicle
- Additional improvements…

Thank you!

Backup slides

Dispenser Improvement Opportunities

There are still several aspects of vehicle and dispenser design which could be modified to further improve the fueling experience.

> Change the tank design and/or modify the code to eliminate the 4500 PSIG restriction
> Inject cool gas into the cylinder (at temperatures below ambient)
> Improve algorithms
  - Incorporate validated heat of compression factors that properly account for temperature of injected gas etc.
  - Eliminate calculation errors
  - Reduce instrumentation error
> Further reduce hydraulic losses in the hose components and on the vehicle

Additional Equipment Improvement Opportunities

- Select the appropriate dispenser design based upon the fueling application
- Reduce the hydraulic losses within the dispenser and hose assemblies by utilizing high flow, low pressure drop components; ANGI has standardized on full flow activated ball valves and tubing with a minimum 1" diameter
- Incorporate the appropriate fueling strategy & algorithm. Percentage of fill before reaching vehicle limitations is affected by the following
  - Initial vehicle tank pressure
  - Tank PRV set point
  - Heat of compression & ambient conditions
  - Hydraulic losses in filling circuit (dispenser & vehicle)

Valve Panels

Compressor

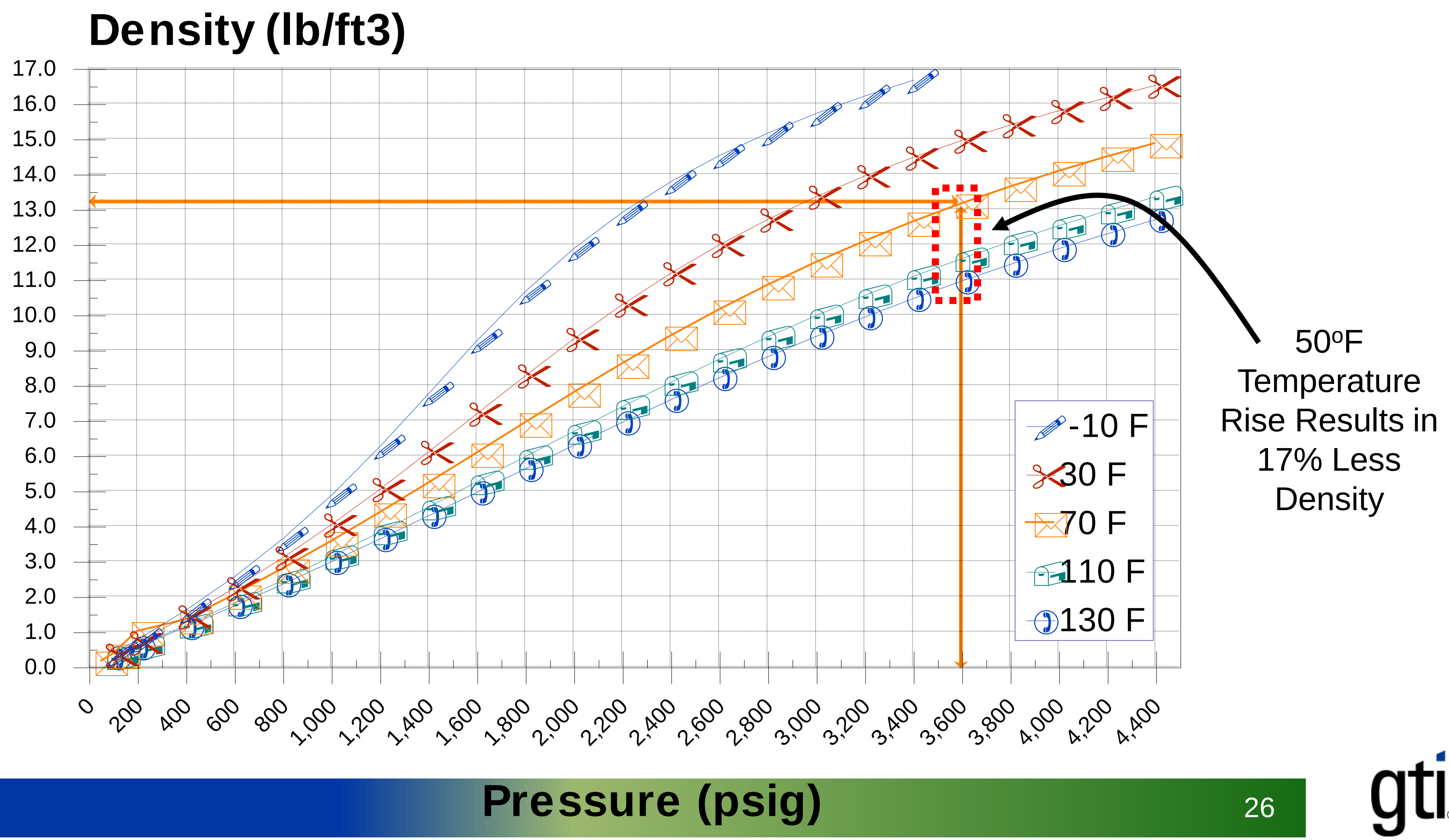
Site & Vehicles

Potential Solutions

- Pre cooling gas before the gas enters the vehicle.
  (Expensive and high maintenance)
- Redundant pressure transducers in the dispenser to provide a more precise measurement of the filling process.
- Raising the relief valve pressure in the dispenser to 5000 psi.
- Tank manufactures using realistic numbers and volumetric numbers that account for the limitations of the technology today. (Useable volume)
- Establishing an industry protocol to measure internal tank pressure and temperature when available.

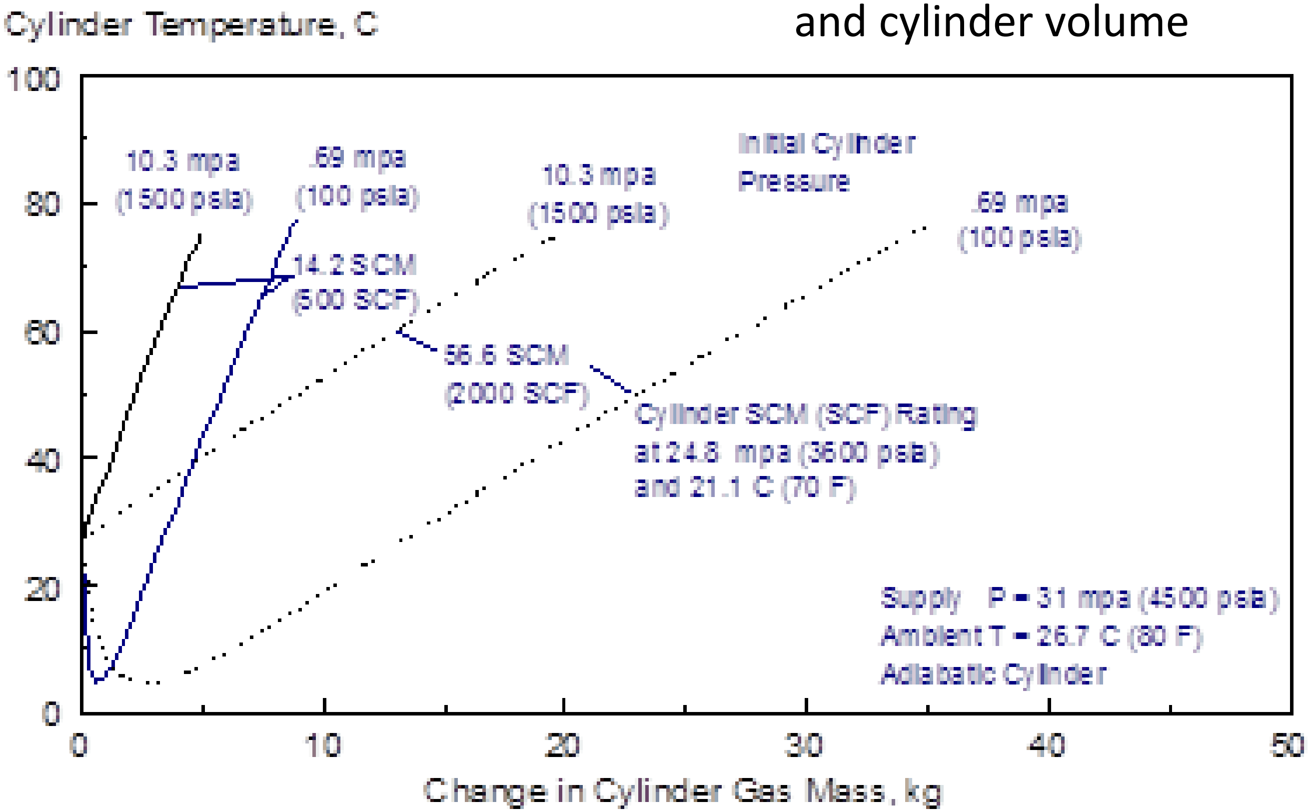
Example: Natural Gas

NGV Fuel Storage Characteristics



Example: Natural Gas

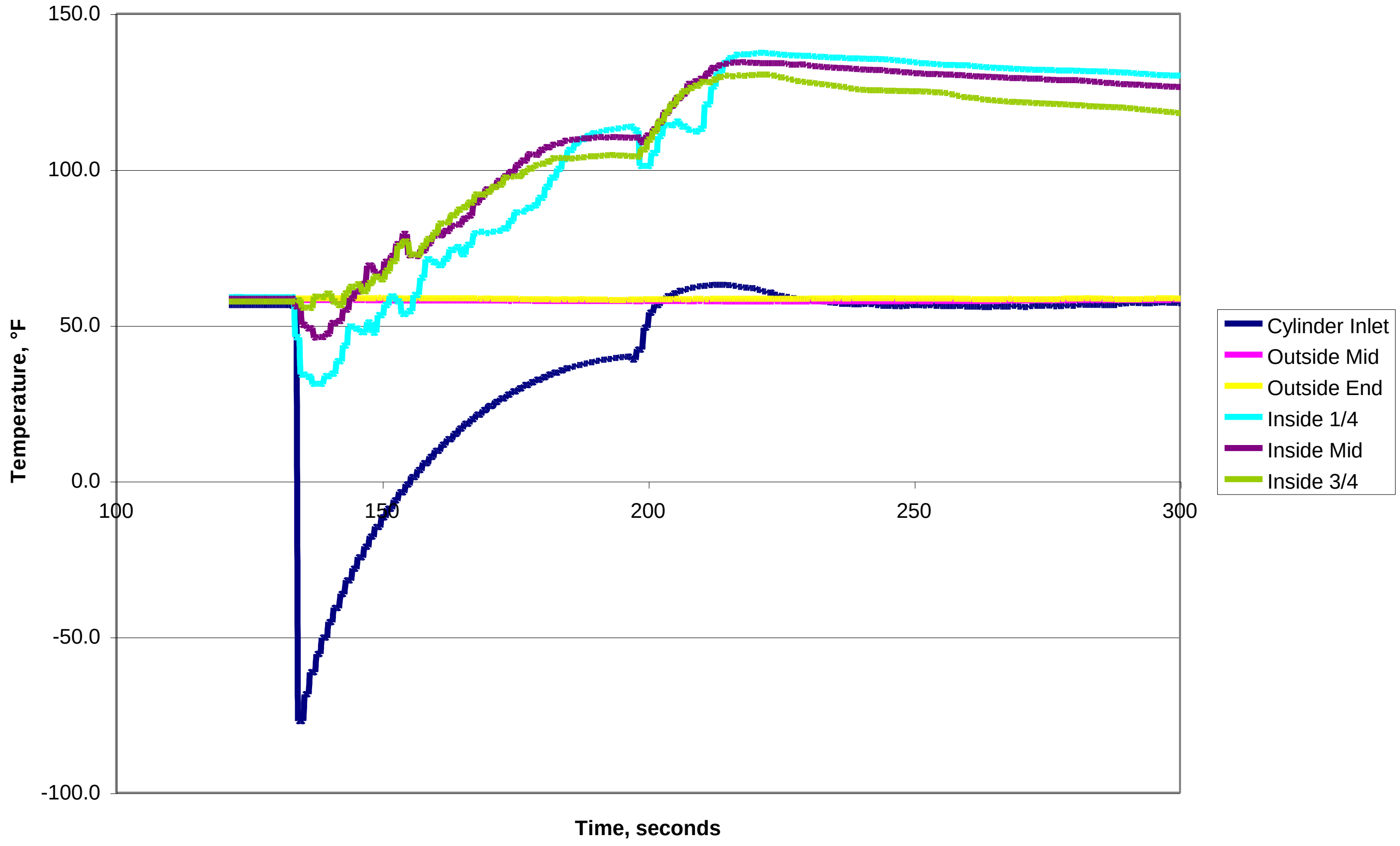
Cylinder temperature is a function of the change in injected gas mass, initial pressure, and cylinder volume



7.8GGE 13.75GGE

When it comes to Temperature….location matters

Example: Type 2 (Steel) – Natural Gas (3000 psig fill pressure)



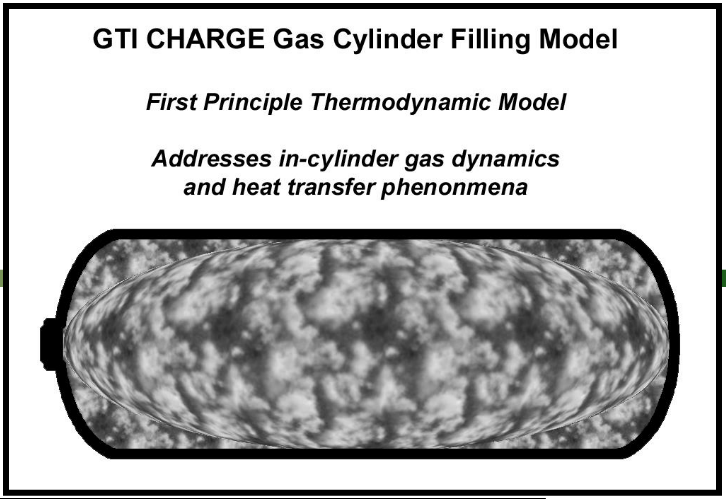
GTI CHARGE Model

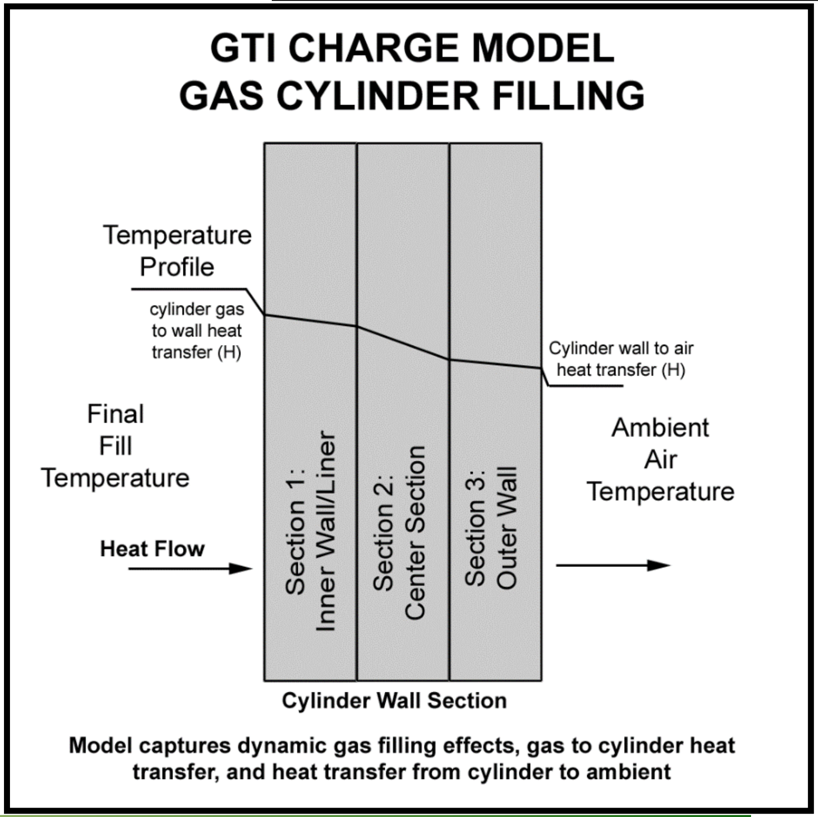
> Modeling Tool
  – Characterizes Dynamic Fast-Fill Process

> Assess Cylinders of Different Size & Construction

> Various Starting & Ending Fill Conditions
  – Cylinders
  – Ground Storage

> Used To Create Dispenser Filling Algorithms





GTI CNG AccuFill® Algorithm

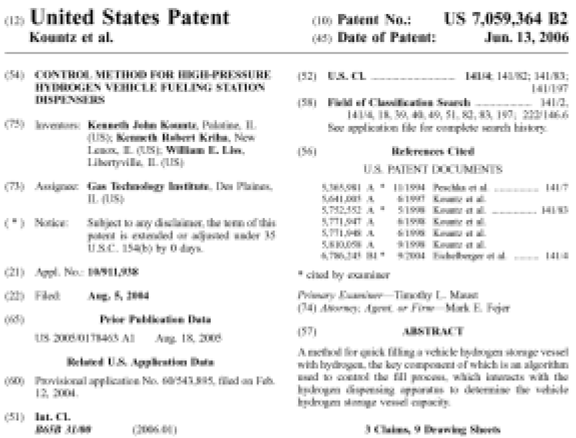
> GTI developed & patented technology to address CNG temperature rise during mid-1990s

> Technology licensed to several worldwide manufacturers, but not integrated

> Provides more consistent fill performance over wide range of ambient conditions

> Tech Transfer to Commercial Dispenser(s) Design Needed.


United States Patent [19]
Kountz et al.
[11] Patent Number: 5,771,948
[45] Date of Patent: Jun. 30, 1998
[54] AUTOMATED PROCESS FOR DISPENSING COMPRESSED NATURAL GAS
[73] Assignee: Gas Research Institute, Chicago, Ill.
[22] Filed: Jun. 19, 1997
Related U.S. Application Data
References Cited
U.S. PATENT DOCUMENTS
[57] ABSTRACT
18 Claims, 14 Drawing Sheets


(12) United States Patent
Kountz et al.
(10) Patent No.: US 7,059,364 B2
(45) Date of Patent: Jun. 13, 2006
(54) CONTROL METHOD FOR HIGH-PRESSURE HYDROGEN VEHICLE FUELING STATION DISPENSERS
(75) Inventors: Kenneth John Kountz, Palatine, IL (US); Kenneth Robert Kriha, New Lenox, IL (US); William E. Liss, Libertyville, IL (US)
(73) Assignee: Gas Technology Institute, Des Plaines, IL (US)
(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.
(21) Appl. No.: 10/911,938
(22) Filed: Aug. 5, 2004
(65) Prior Publication Data
US 2005/0178463 A1 Aug. 18, 2005
Related U.S. Application Data
(60) Provisional application No. 60/543,895, filed on Feb. 12, 2004.
(51) Int. Cl.
(56) References Cited
U.S. PATENT DOCUMENTS
* cited by examiner
Primary Examiner—Timothy L. Maust
(74) Attorney, Agent, or Firm—Mark E. Fejer
(57) ABSTRACT
A method for quick filling a vehicle hydrogen storage vessel with hydrogen, the key component of which is an algorithm used to control the fill process, which interacts with the hydrogen dispensing apparatus to determine the vehicle hydrogen storage vessel capacity.
3 Claims, 9 Drawing Sheets