Manufacturing Cost Estimation for Class 2B/3 CNG Systems

United States
Environmental Protection
Agency

Manufacturing Cost Estimation for Class 2B/3 CNG Systems

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
FEV North America, Inc.
EPA Contract No. EP-C-12-014 WA2-03

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

United States Environmental Protection Agency

EPA-420-D-15-004
June 2015

Table of Contents

List of Figures

List of Tables

Executive Summary

The United States Environmental Protection Agency (EPA) contracted with FEV North America, Inc., to determine incremental direct manufacturing costs for a complete CNG fuel system. The system selected to represent the light-duty vehicle segment was a 2013 Chevrolet Silverado equipped with General Motors Bi-Fuel option. The Silverado was purchased by FEV and all CNG related components were identified. The vehicle was then completely disassembled. Names, photos and weights were assigned to all CNG related components and compiled in a Bill of Materials (BOM). All CNG system components were reviewed in detail and cost estimated using FEV's standard costing process. All costs were developed using a volume assumption of 450,000 units per year. This cost analysis is inclusive of all associated assembly cost from component to vehicle. Calculations were performed to determine equipment sizing, cycle times and material usage requirements. FEV utilized its extensive database of rates for equipment, labor, material, end item scrap, selling, general and administrative (SG&A), profit, and engineering, design and testing (ED&T) to develop costs representative of what an OEM would incur for such a system in high volume automotive manufacturing.

Cost for the five (5) subsystems are as follows:

1. Storage-$1,360
2. Safety Devices-$151
3. High Pressure Circuit-$184
4. Low Pressure Circuit-$278
5. Controls-$303

Total System cost = **$2,276**

Sixty (60) percent of the system cost can be attributed to CNG storage. Gasoline's 17x energy density factor over natural gas at atmospheric conditions creates a storage challenge for CNG. High pressure storage (3600psi) is required to minimize this energy density differential. Pressure, weight, and safety requirements all contribute to CNG tank costs. The one-piece, seamless, carbon fiber reinforced tank undergoes a twelve (12) step manufacturing process before completion. In light of carbon fiber processing improvements like pre-preg fibers, the process of wrapping is a time consuming cost driver. Make up 44% of the tank cost. The wrapping process and material cost of carbon fiber.

The System is comprised of: high pressure lock-off, pressure relief device, and excess flow valve.
High Pressure Circuit includes; refueling filler, fuel lines, filter and pressure regulator.
Low Pressure Circuit includes; fuel lines, fuel rails and CNG injectors.
Controls include; ECU, intake air temperature module, fuel pump module, and wiring.

General Motors Bi-Fuel System was designed as an add-on to an existing gasoline engine. As an add-on, the CNG system has its own ECU requiring Intake Air Temperature and Fuel Pump control modules. A dedicated CNG system would eliminate these components, reducing overall vehicle cost.

1. Introduction and Program Objectives

1.1. Objective

The objective of this study is to develop cost for a complete light-duty truck CNG system, manufactured at high production volume (450,000 units per year).

1.2. Vehicle Selection

A 2013 Silverado 2500 4WD LT Extended CAB truck with bi-fuel option was selected as a representative light-duty passenger vehicle CNG system. The truck was equipped with a 6.0L Vortec engine, GM designation LC8. The CNG system is modular and was designed as an add-on option to GM's existing product.

Figure 1- Chevrolet Silverado 2500 CNG

(Source: FEV, Inc. photos)

1.3. Background

For the same energy output, combustion of CNG produces 29% less carbon dioxide than combustion of oil base fuels (i.e., gasoline). 'In most applications, using natural gas produces less of the following substances than oil or coal: carbon dioxide (CO2), the primary greenhouse gas; sulfur dioxide, which is the primary precursor of acid rain; nitrogen oxides, which is the primary precursor of smog; and particulate matter, which can affect health and visibility.'

http://www.aga.org/our-issues/issuesummaries/Pages/EnvironmentalBenefitsofNaturalGas.aspx

In 2013 the US consumed 3.2 billion barrels of gasoline as shown in **Table 1**. In addition to fuel reduction technologies like turbo-downsizing and lightweighting, CNG offers another option to reducing petroleum-based fuel consumption.

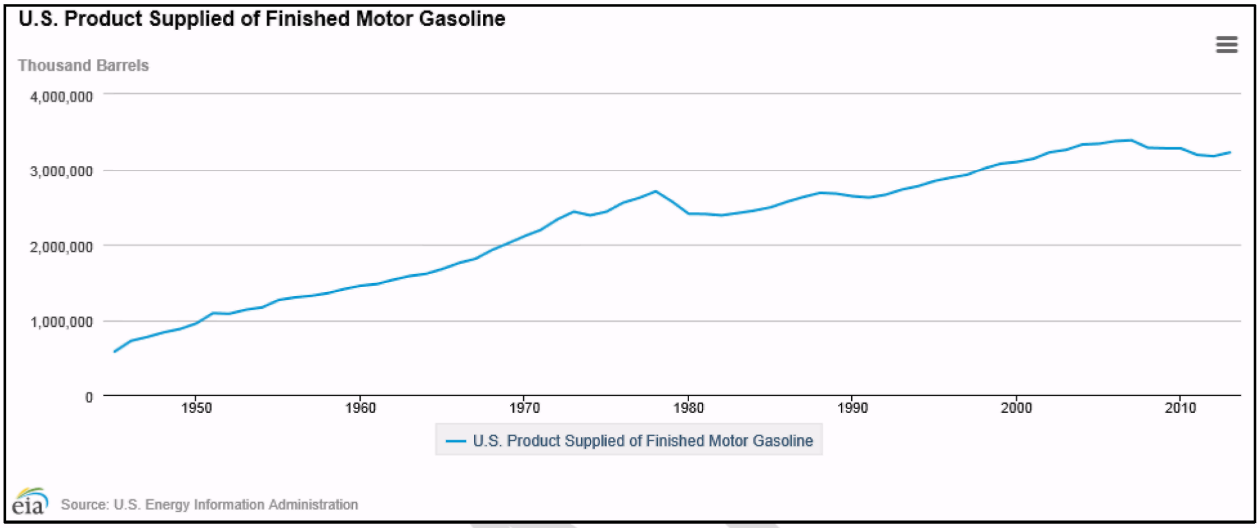

Table 1- U.S. Product Supplied of Finished Motor Gasoline

http://www.eia.gov/tools/faqs/faq.cfm?id=23&t=10

‘CNG conversions can provide stability against fluctuating fuel prices as well as lower vehicle operating costs for fleet administrators. CNG sells for an average of $2.10 per Gasoline Gallon Equivalent (GGE), and is as low as $1 in some parts of the country, representing a significant savings over unleaded regular fuel. The national price range for unleaded regular fuel is $2.25 - $3.50 per gallon’.

http://corporate.ford.com/news-center/press-releases-detail/first-cng-capable-2014-ford-f-150-rolls-off-the-line-in-kansas

Storing enough natural gas in a motor vehicle to provide a sufficient range is a challenge with CNG. To improve upon its lower energy density, natural gas is stored at 3600 psi. Even at this pressure fuel tank size is significantly larger. For example the Silverado CNG tank is rated at 17 GGE gallons however, the actual internal tank volume as measured after sectioning by FEV is approximately 55 gallons. GGE is based on an equal measure of energy making it possible to compare cost per unit of alternate fuels, GGE in terms of CNG Gas (Volume/Pressure/Temp) = 1 Gallon of Gas (Temp, Pressure=atm). For example 1 GGE of CNG and 1 gallon of gasoline are equivalent.

At this time, the primary drawbacks of CNG are the underdeveloped vehicle refueling infrastructure and the fuel storage requirements. As of 2013 there were approximately 1,260 CNG refueling stations in the country.

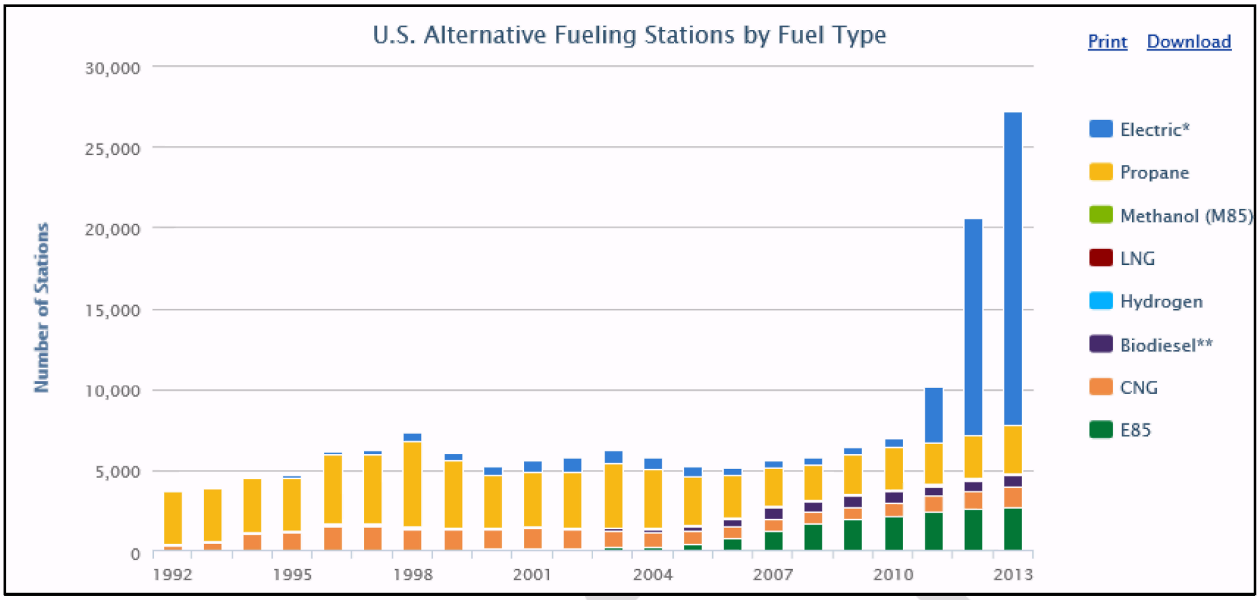

Table 2- U.S. Alternative Fueling Stations by Fuel Type

http://www.afdc.energy.gov/data/10332

Implementing a high pressure CNG system in a passenger vehicle requires safety provisions not needed with conventional gasoline. Directly mounted to the CNG tank are two (2) safety devices. The first is an electronic flow lock preventing CNG from leaving the tank unless permitted by the ECU. The second is a pressure relief valve with back-up burst disc to prevent overpressure in the CNG system. A manual isolation valve is located after the tank for service and an additional electronic flow lock is located in the pressure regulator. A flow fuse is used to cut-off flow in the event the system is ruptured and the intended gas flow rate is exceeded.

Higher combustion temperatures and corrosive properties of natural gas require hardened exhaust valves and intake/exhaust valve seats.

http://www.gmfleet.com/vehicle-overviews/fuel-efficiency/bi-fuel.html

2. System Overview & Cost Structure

2.1. System Design

Figure 2 is a schematic representation of the CNG system generated as an aid to understand the components and their function. The system was broken into five (5) subsystems and color coded at the bottom of the figure. The CNG tank manages fuel pressures up to 3600 psi when full. Directly mounted to the CNG tank are the Safety Relief Valve and High Pressure Lock-off (HPL) solenoid.

Connecting to the underbody purge line is the safety relief assembly. A spring piston with plastic face seal opens when the tank pressure exceeds the design limit. Over temperature conditions exceeding the melting point of the plastic face seal will also open this valve. The pressure burst disc is a secondary safety device protecting the tank from over pressure.

The opposite end of the tank mounts the HPL solenoid. This valve requires activation before any gas is permitted to exit the tank. Integrated into this assembly is a manual purge valve, providing a means to vent the system to the atmosphere, and a temperature transmitter extending into the tank cavity.

Following the HPL solenoid is the excess flow valve. This device protects the system from a downstream rupture. If the gas flow exceeds the limit of this valve it closes. When pressure across the valve equalizes the valve automatically resets.

The fill circuit consists of a quick release with integrated check valve for ensuring one-way flow. The quick release serves as the connection point for refueling. A secondary check valve located after the quick release again ensures one-way flow. The fill circuit continues to the tank with reverse flow through both the excess flow valve and HPL solenoid.

Continuing from the excess flow valve, fuel travels through a manual ball (service) valve to the filter before entering the pressure regulator. Integrated into the pressure regulator is a normally closed solenoid valve in addition to pressure and temperature transmitters. The solenoid valve provides another level of security from unintended fuel flow. Heat absorption caused by the expansion of gas requires a heating circuit which ties into the engine cooling system. The pressure regulator reduces pressure to 100 psig.

Following the pressure regulator, fuel is routed to the fuel rails supplying eight (8) individual CNG injectors. The injectors terminate via hose to port mounted nozzles in the intake manifold.

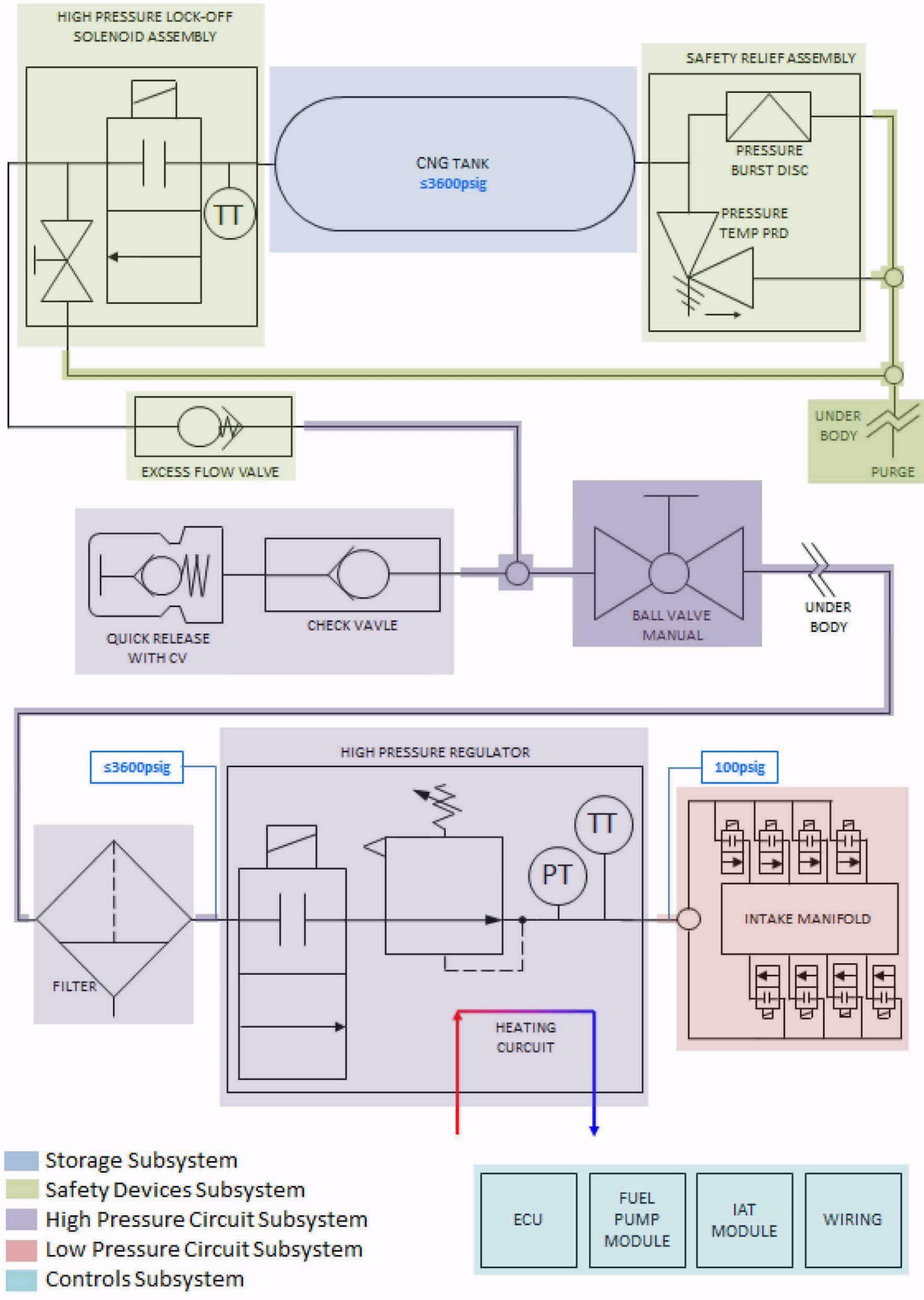

Figure 2- Compressed Natural Gas (CNG) System

(Source: FEV, Inc. photos)

2.2. Hardware

Primary CNG hardware is shown in **Figure 3** in order as follows:

- Type 3 CNG Tank
    - Manufacturer: Structural Composites Industries; P/N:319875
    - Construction: Seamless Aluminum, Carbon Fiber reinforced
- High Pressure Lock-Off (**HPL**)
    - Manufacturer: GFI Control Systems; P/N:PT13F0172
    - Construction: Billet Aluminum
    - Features: Temperature Measurement, Manual Purge Valve
- Pressure Relief Device (**PRD**)
    - Manufacturer: GFI Control Systems; P/N:PRD-120BD
    - Construction: Billet Aluminum
- Flow Fuse
    - Manufacturer: HOKE; P/N:HVX316
    - Construction: 316 stainless steel, brass, Monel®, Hastelloy® C-276
- Distribution Lines
    - Seamless Stainless Steel & Stainless Steel Jacketed PTFE
- Filter
    - Manufacturer: Parker; P/N:FFC-112 SAE-10
    - Construction: Billet Aluminum, Coalescing Media Filter
- High Pressure Regulator (**HPR**)
    - Manufacturer: GFI Control Systems; P/N:P214-980
    - Construction: Forged Aluminum
    - Features: High Pressure Shut-Off Solenoid, High Pressure Transducer, MAP referencing
- Fuel Rail
    - Billet Aluminum
- Fuel Injector
    - Manufacturer: AC Delco; P/N:22991067
- Engine Control Unit (**ECU**)
    - Manufacturer: Fly SF; P/N:028705/9-V
- Control Modules – Intake Air Temperature (**IAT**), Fuel Pump
    - Manufacturer: IMPCO Automotive; P/N: MD-53497-001, MD-54548-001
- Wiring

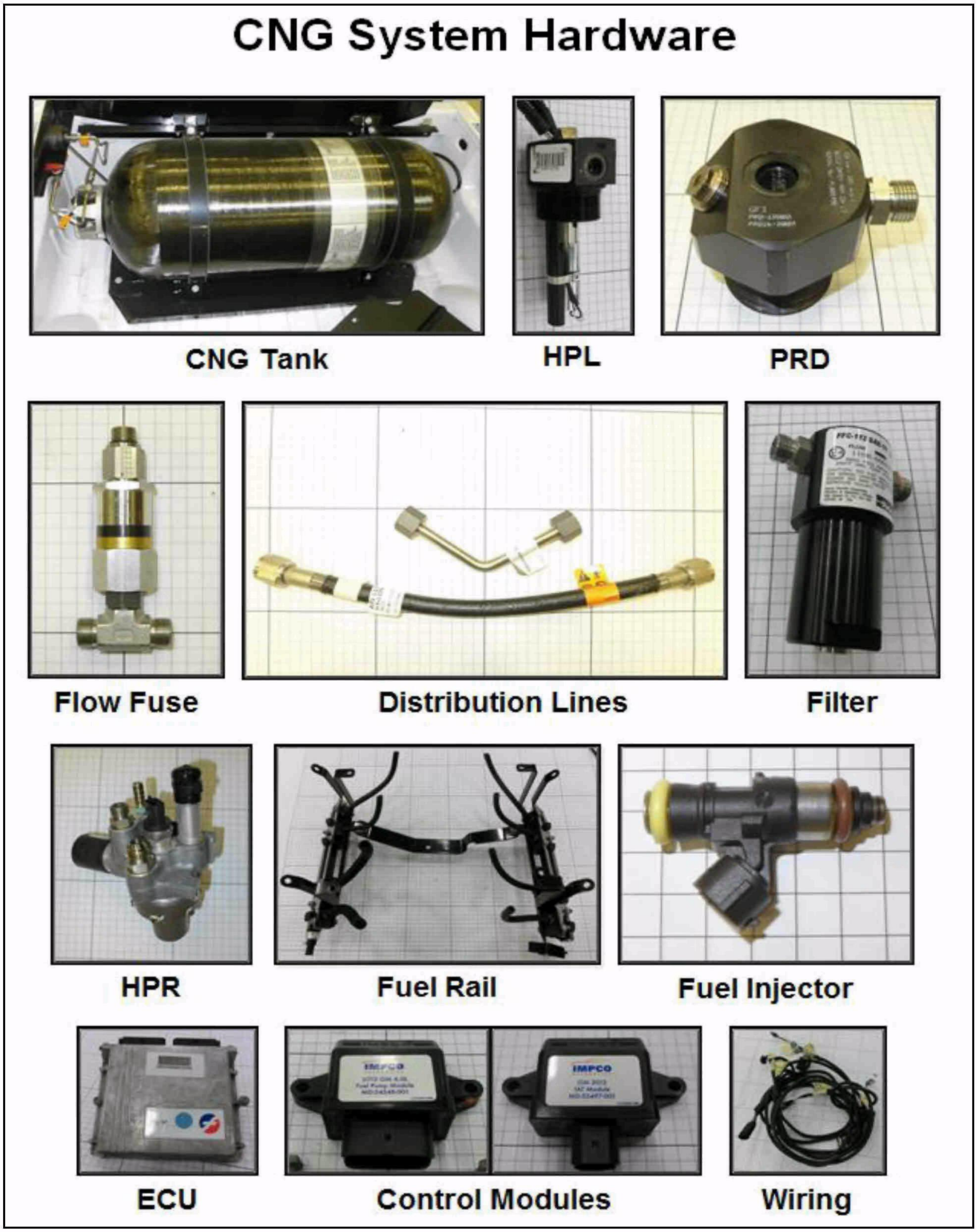

Figure 3- CNG System Hardware

(Source: FEV, Inc. photos)

2.3. BOM Creation

The CNG system was disassembled starting with the tank, following the flow path, and ending with the fuel injectors. Assemblies were removed from the vehicle in groups that were thought to represent actual assembly. After removal from the vehicle assembles/components were photographed, weighed and tagged.

The first step in disassembly of the CNG system was to purge all CNG from the tank. This was done by releasing the manual purge valve and deactivating the solenoid lock-off valve. Next, the tank, cradle and related hardware were removed from the bed of the truck. Subsequently in conjunction with another study the entire truck was disassembled and all CNG related system components were removed, named, photographed, weighted and logged into a Bill of Material (BOM).

The CNG system was categorized into five (5) main Sub-Systems: Storage, Safety Devices, High Pressure Circuit, Low Pressure Circuit, and Controls. The storage subsystem includes the tank cover, tank cradle, and tank. The Safety Devices subsystem includes the high pressure lock-off, high pressure relief device, and excess flow valve. The high pressure circuit includes all high pressure fuel lines as well as fuel filter and pressure regulator. The low pressure circuit includes all low pressure fuel lines as well as cooling lines associated with the pressure regulator heating circuit. Also included in this subsystem are the fuel rail and fuel injectors. The wiring harness, control modules and ECU are included in the Controls Subsystem.

The BOM structure shown in **Table 3** details the subsystems and Sub-Subsystems which can be identified in the system schematic as segregated color shaded areas. The ‘Purge’ and ‘Distribution, Low Pressure’ Sub-Subsystems are shaded darker to highlight included plumbing.

Every Sub-Subsystem, assembly, or component listed in the BOM features: mass, photo link, cost, and quote link.

Part Numbering			Part Name/Description	QTY	Attribute Data
			Product Structure		Mass
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"
20	00	00	**Compressed Natural Gas System**		**239.334**
20	01	00	**Storage Subsystem**	1	**209.889**
20	01	01	Tank Cover Sub-Subsystem	1	33.650
20	01	02	Cradle Sub-Subsystem	1	78.280
20	01	03	Tank Sub-Subsystem	1	97.959
20	02	00	**Safety Devices Subsystem**	1	**6.603**
20	02	01	High Pressure Lock-Off Valve (HPLV) Sub-Subsystem	1	3.676
20	02	02	Safety Relief Valve Sub-Subsystem	1	1.004
20	02	03	Excess Flow Valve Sub-Subsystem	1	0.463
20	02	04	Purge Sub-Subsystem	1	1.460
20	03	00	**High Pressure Circuit Subsystem**	1	**7.732**
20	03	01	Filler (Refueling) Sub-Subsystem	1	0.637
20	03	02	Distribution, High Pressure Sub-Subsystem	1	2.387
20	03	03	Filter Sub-Subsystem	1	0.613
20	03	04	Pressure Regulator Sub-Subsystem	1	4.095
20	04	00	**Low Pressure Circuit Subsystem**	1	**8.622**
20	04	01	Distribution, Low Pressure Sub-Subsystem	1	4.621
20	04	02	Fuel Rails Sub-Subsystem	1	3.825
20	04	03	Fuel Injectors Sub-Subsystem	8	0.176
20	05	00	**Controls Subsystem**	1	**6.488**
20	05	01	Control Module Sub-Subsystem	1	3.688
20	05	02	Wire Harnesses Sub-Subsystem	1	2.800

Table 3- BOM Compressed Natural Gas (CNG) System

2.4. Costing Methodology

This cost analysis is a full system complete evaluation inclusive off all hardware associated with the CNG system. Included in the cost is component assembly to the vehicle. The CNG system as analyzed is a low-volume design, often utilizing off-the-shelf hardware. On specific components, where a high volume manufacturing choice was clear, alternative manufacturing assumptions were made. For example, the safety relief protection collar was manufactured from billet however it was quoted as a die casting. Such assumptions are noted in detail throughout the body of this report. The volume assumption for cost estimation was 450,000 vehicles per year.

Costs were developed for all critical components by detailing each operation in a Manufacturing Assumptions Quote Sheet (MAQS). Process calculators were used to determine equipment size and corresponding rate ($/hr), cycle time (seconds) and material usage (kg). For example, the Pressure Regulator Cap was identified as an aluminum die casting. The number of slide pulls, cavities, part width, part height, average wall thickness, parting line area, cavity surface area, and max wall thickness were all used to determine the die-casting machine size, cycle time and material usage. This information was then transferred to the MAQS where rates are pulled in for material, labor, manufacturing overhead/burden, end item scrap, SG&A, profit, and ED&T. Cost contributions are then calculated for these core cost elements. Similar process calculators are used for subsequent processing such as machining, where all machine features are measured, speed and feed rates assigned based on the respective material, and feed times calculated. In addition pallet changes, tool changes, rapid times, as well as estimated work pieces per fixture are used to estimate the total cycle time. Finally all processes are summed, end item packaging estimated, and total cost calculated. Cost contributions for the core cost elements are then linked to the Cost Model Analysis Template (CMAT). The CMAT incorporates cost data from various Sub-Subsystems into one summary sheet. Process costs were estimated as follows:

1. Detailed assessment of manufacturing processes used to create the component
2. Populate appropriate process calculator, identifying equipment size, cycle time, and material usage
3. Transfer data from step 2 into quotation sheet and assign labor resources
4. Repeat for all manufacturing processes required
5. Repeat for all components in Sub-Subsystem
6. Evaluate Sub-Subsystem assembly requirements including: number of stations, level of automation, burden rate, number of operators, and cycle time
7. Evaluate vehicle assembly requirements including: number of stations, level of automation, burden rate, number of operators, and cycle time
8. Assess packaging needs and estimate packaging costs

3. Storage Subsystem

The storage subsystem includes all hardware associated with the CNG tank. It is subdivided into the following Sub-Subsystems:

- Tank Cover Sub-Subsystem
- Cradle Sub-Subsystem
- Tank Sub-Subsystem

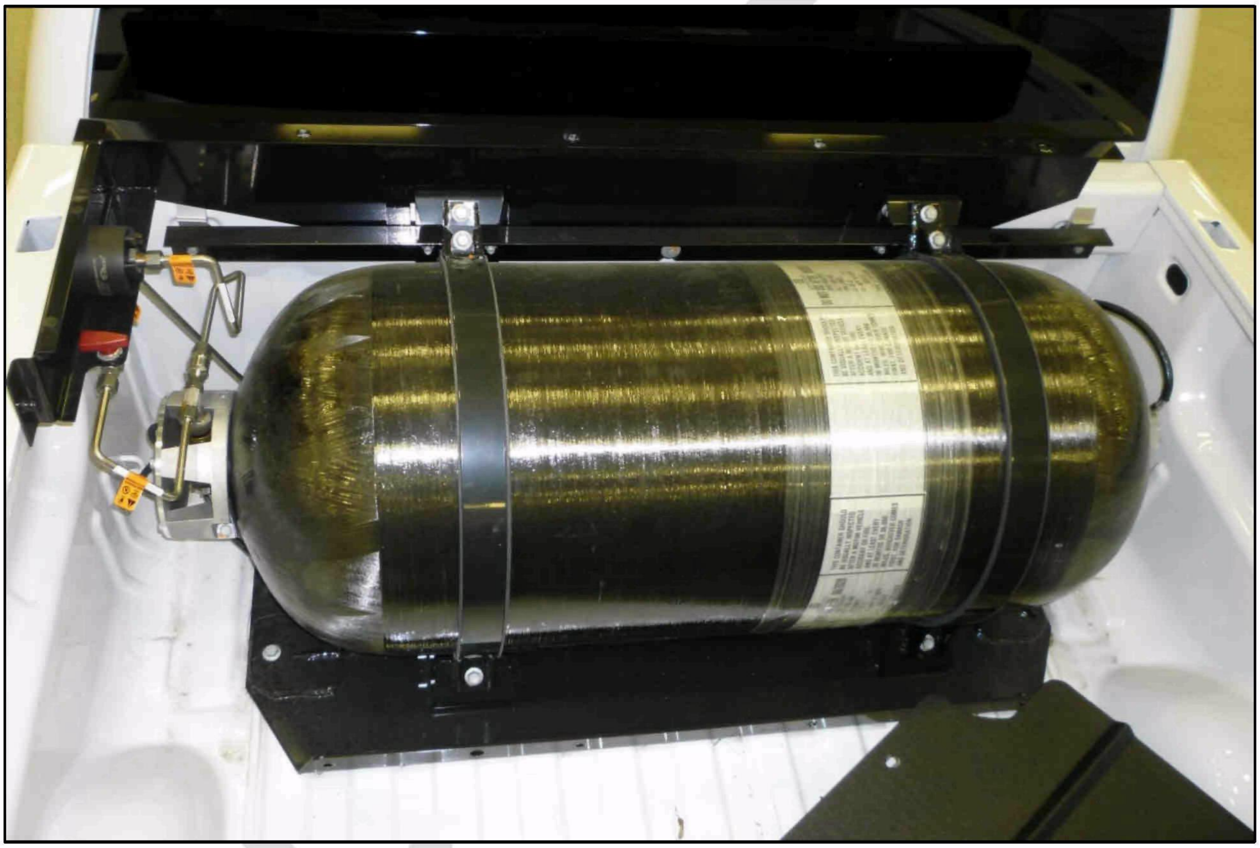

Figure 4- Storage Subsystem

(Source: FEV, Inc. photos)

3.1. Tank Cover Sub-Subsystem

Figure 5 shows the tank cover as assembled in the bed of the Silverado. The cover fastens to the cradle and cover mount bracket.

Figure 5- Tank Cover Sub-Subsystem – Assembled

(Source: FEV, Inc. photos)

The Tank Cover Sub-Subsystem includes the fabricated diamond plate aluminum tank cover with access door, steel bracket, and associated fasteners as shown in **Figure 6**. For high volume production the Tank Cover was estimated as multiple stampings assembled as a weldment. The cover mount was heavy gauge material and also processed as a multiple stamping weldment.

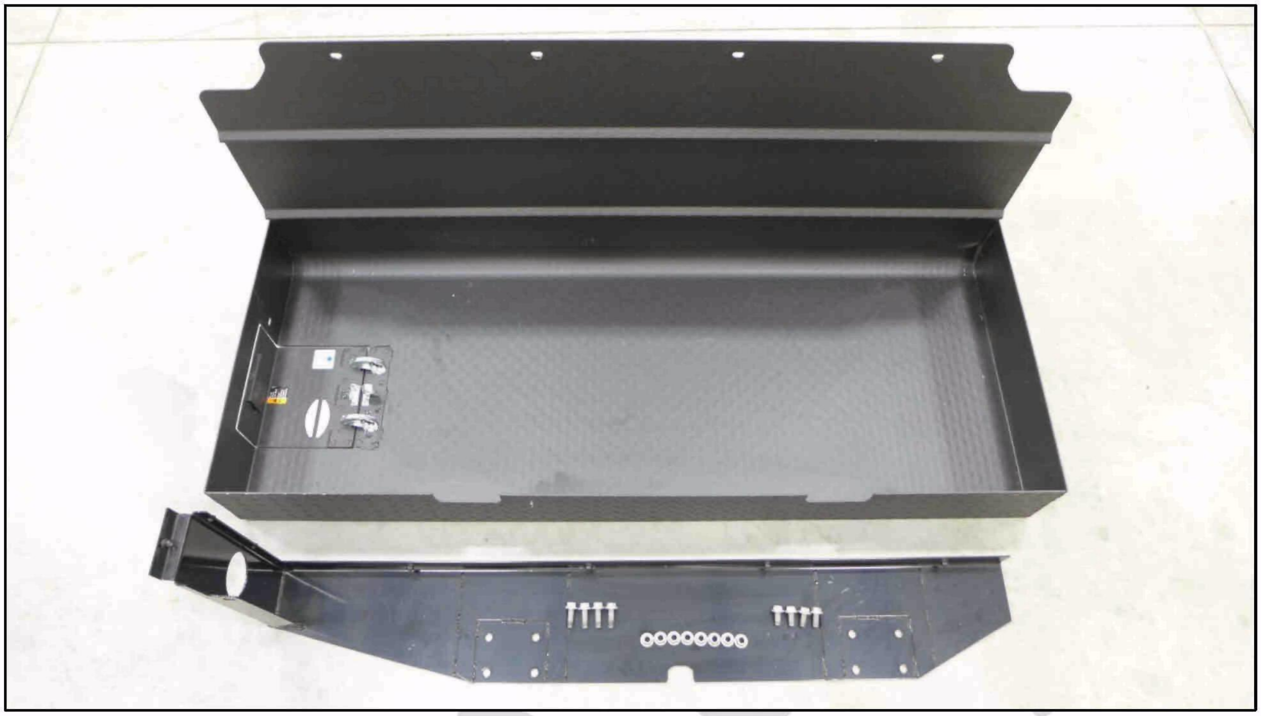

Figure 6- Tank Cover Sub-Subsystem – Components

(Source: FEV, Inc. photos)

The bill of materials for Tank Cover Sub-Subsystem is shown in **Table 4**. Sub-Subsystem mass is 33.7 kg and the cost is $94.

Part Numbering: System	Part Numbering: Subsystem	Part Numbering: Sub-Subsystem	Part Name/Description (Product Structure: System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 2 3 4 5 6 7 8 9 10)	QTY: Quantity	Attribute Data: Mass: Total Mass (Unit Mass x qty.) "kg"	Cost Analysis: Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**			
20	**01**	**00**	**Storage Subsystem**	1		
20	**01**	**01**	**Tank Cover Sub-Subsystem**	1	**33.650**	**$94**
20	01	01	Tank Cover	1	21.508	
20	01	01	Bolt, Tank Cover	9	0.189	
20	01	01	Cover Mount, Cradle, Tank	1	11.425	
20	01	01	Bolt, Long, Cover Mount, Cradle, Tank	4	0.198	
20	01	01	Bolt, Short, Cover Mount, Cradle, Tank	4	0.157	
20	01	01	Nut, Cover Mount, Cradle, Tank	8	0.173	

Table 4- BOM Tank Cover Sub-Subsystem

3.2. Cradle Sub-Subsystem

The Cradle bolts into the box of the truck and serves as a mounting structure for the tank. The tank is secured to the cradle with two (2) rubber lined straps fastened with bolts. Cradle Sub-Subsystem components are shown in **Figure 7.**

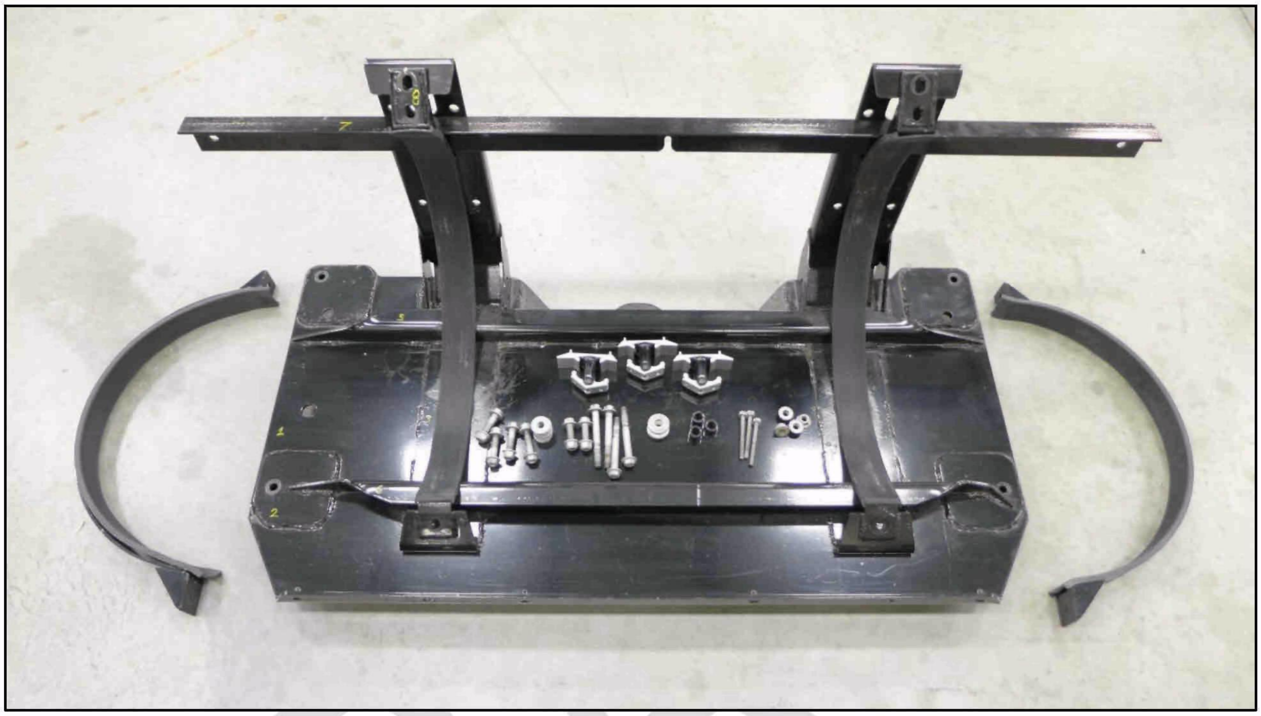

Figure 7- Cradle Sub-Subsystem – Components

(Source: FEV, Inc. photos)

The Cradle Sub-Subsystem is a weldment of thirteen (13) individual stampings. Three (3) sprung retaining mechanisms were used to attach the cradle to the back of the truck box. These retainers were estimated by assuming a clipnut for high volume production.

The bill of materials for the Cradle Sub-Subsystem is shown in **Table 5**. Sub-Subsystem mass is 78.3 kg and the cost is $193.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**01**	**01**	**Tank Cover Sub-Subsystem**	1	**33.650**	20 01 01	
20	**01**	**02**	**Cradle Sub-Subsystem**	1	**78.280**	20 01 02	**$193**
20	01	02	Bolt, Cradle, CNG Tank, Bottom	4	0.421	CIMG0020	
20	01	02	Washer, Cradle, CNG Tank, Bottom	4	0.085	CIMG0021	
20	01	02	Retainer Assembly, Cradle, CNG Tank, Back	3	0.517	CIMG0029	
20	01	02	Collar, Cradle, CNG Tank, Back	3	0.090	CIMG0030	
20	01	02	Bolt, Cradle, CNG Tank, Back	3	0.096	CIMG0032	
20	01	02	Washer, Cradle, CNG Tank, Back	1	0.012	CIMG0033	
20	01	02	Nut, Cradle, CNG Tank, Bottom	4	0.087	CIMG0035	
20	01	02	Bolt, Strap, CNG Tank	4	0.325	CIMG0101	
20	01	02	Washer, Strap, CNG Tank	18	0.167	CIMG0102	
20	01	02	Straps, CNG Tank	2	4.221	CIMG0103	
20	01	02	Bolt, Welded Strap, CNG Tank	2	0.150	CIMG0110	
20	01	02	Cradle, CNG Tank	1	72.109	CIMG0112	

Table 5- BOM Cradle Sub-Subsystem

3.3. Tank Sub-Subsystem

The CNG tank used on Silverado is a type 3 container made by Structural Composite Industries, a Worthington Cylinders Company as shown in **Figure 8**. CNG cylinders are available in 4 types, with type 1 being the heaviest and least expensive to type 4 being the lightest and most expensive. Type 3 tanks have a seamless and gas tight metal liner reinforced by composite wrap around the entire tank. The tank has a 15 year service life after which the tank must be replaced. Type 3 CNG tanks are pressure rated for 3600psi and are tested at 5500psi. Worthington manufactures all their cylinders to aviation standards, with a burst safety factor of at least 3.0 and with design verification impact testing about the full cylinder periphery.

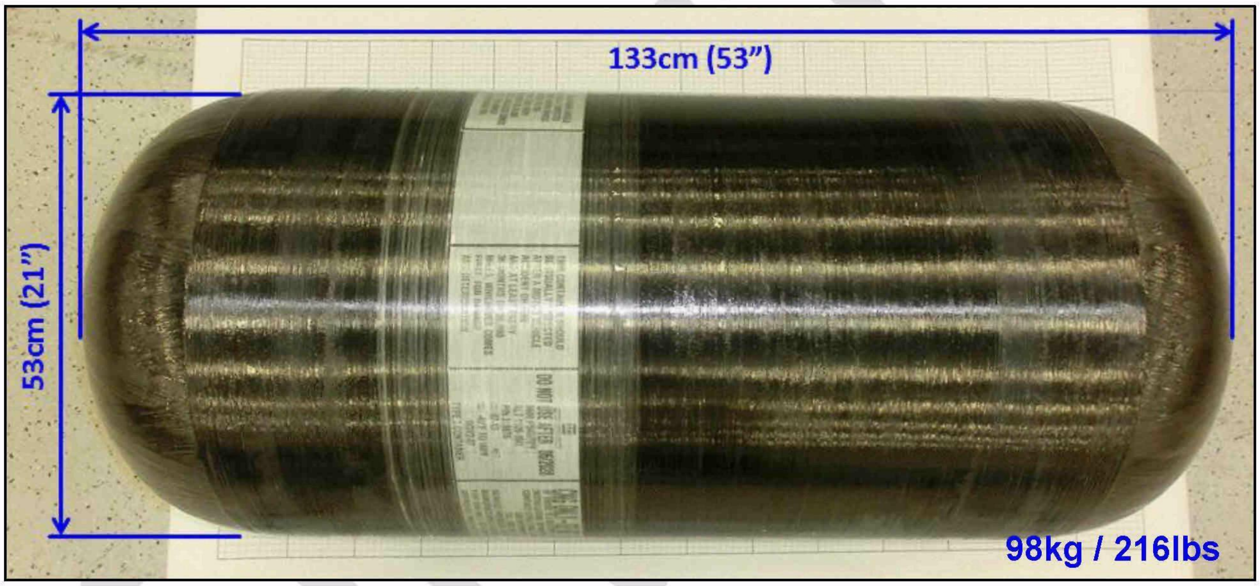

Figure 8- CNG Tank

(Source: FEV, Inc. photos)

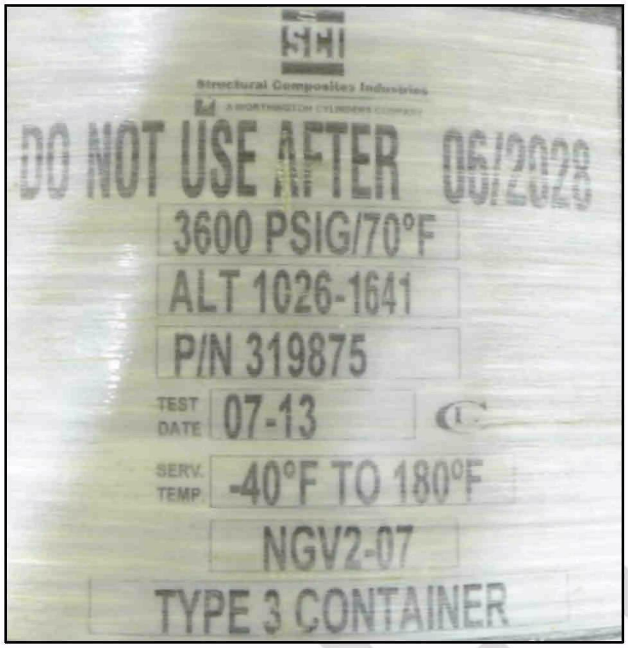

Figure 9- CNG Tank Label

(Source: FEV, Inc. photos)

Figure 9 show the label **Figure 10** show the Silverado CNG Tank sectioned lengthwise. Composite wrap thickness thins around the radius and thickens around the ends of the tank.

Figure 10- Silverado CNG Tank Section # 1

(Source: FEV, Inc. photos)

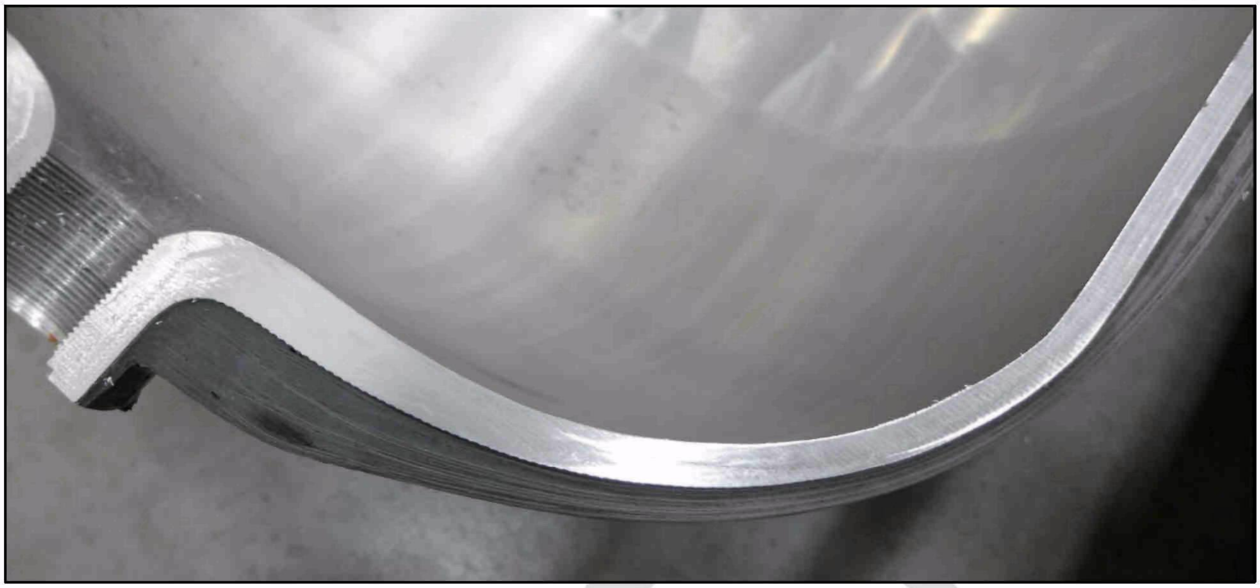

Figure 11- Silverado CNG Tank Section # 2

(Source: FEV, Inc. photos)

Steps and images for CNG tank manufacturing are outlined below:

Step 1: Saw seamless aluminum tube

Step 2: Ultrasonic scanning of tube for imperfections

Step 3: Preheat tube to initiate forming

Step 4: Spin forming

Step 5: Stress relief

Step 6: Machine neck threads

Step 7: Apply corrosion protectant

Step 8: Composite carbon fiber wrap

Step 9: Resin coating

Step 10: Oven cure resin

Step 11: Hydrostatic leak test

Step 12: Random sample burst test

http://www.youtube.com/watch?v=XxRiyCGtKgo

Figure 12- Step 1: Seamless Aluminum Tube Cut to Length

http://www.youtube.com/watch?v=-NDvGYfwTxs

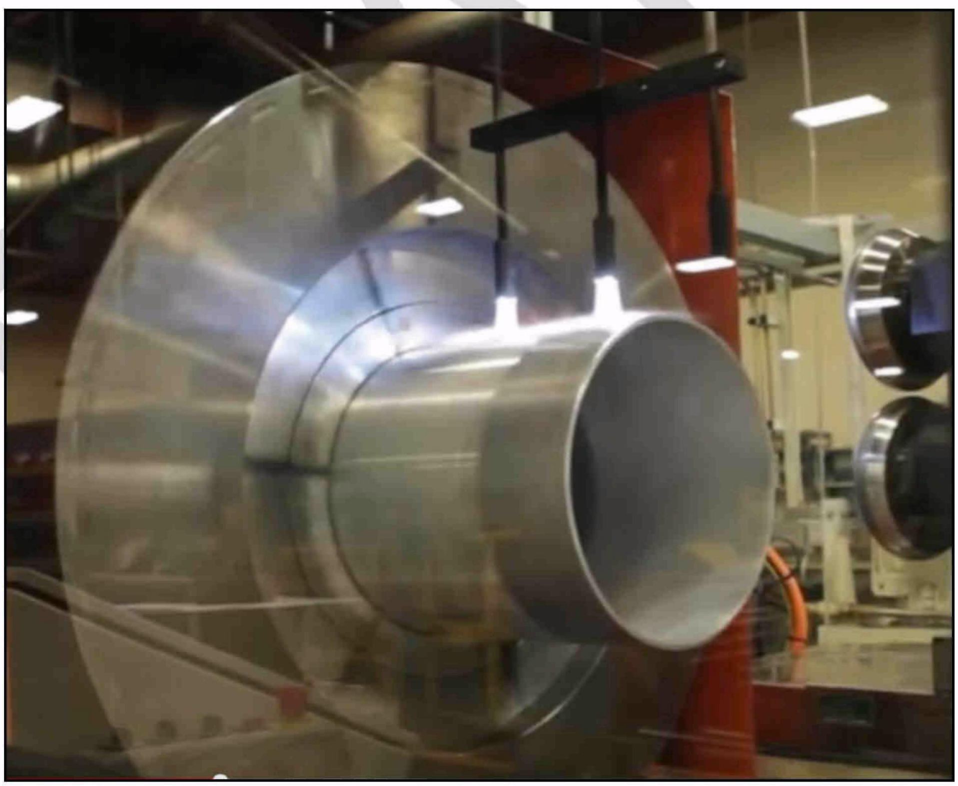

Figure 13- Step 3: Preheating of Blank Prior to Spin Form

http://www.youtube.com/watch?v=XxRiyCGtKgo

Figure 14- Step 4: Blank Chucked in Spin Form Machine

http://www.youtube.com/watch?v=-NDvGYfwTxs

Figure 15- Step 4-1: Spin Forming

http://www.youtube.com/watch?v=-NDvGYfwTxs

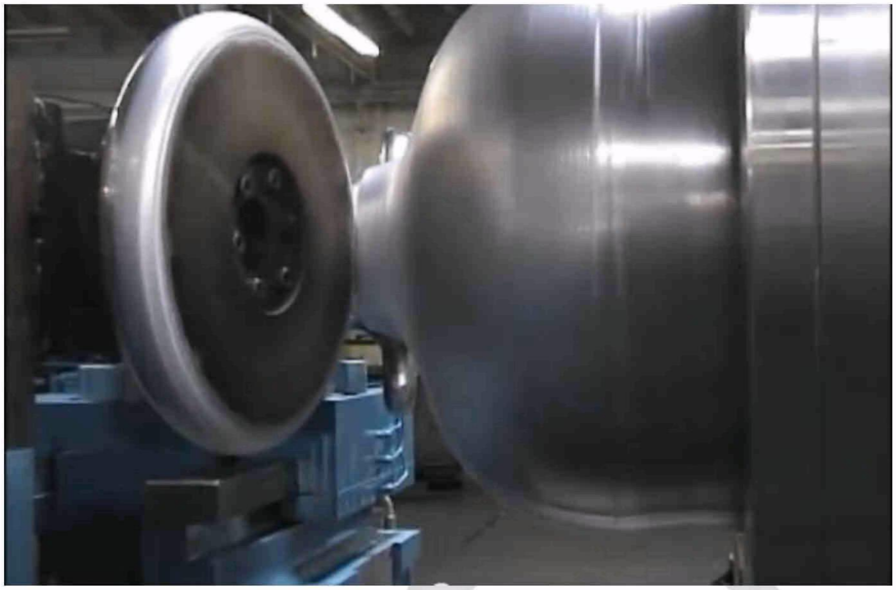

Figure 16- Step 4-2: Spin Forming

http://www.youtube.com/watch?v=-NDvGYfwTxs

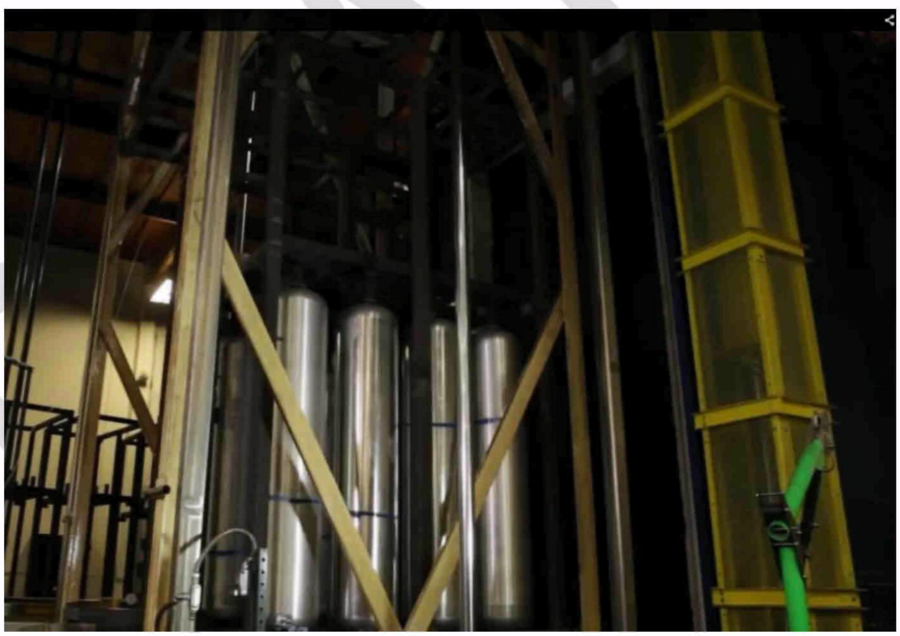

Figure 17- Step 5: Heat Treatment (Stress Relief)

http://www.youtube.com/watch?v=XxRiyCGtKgo

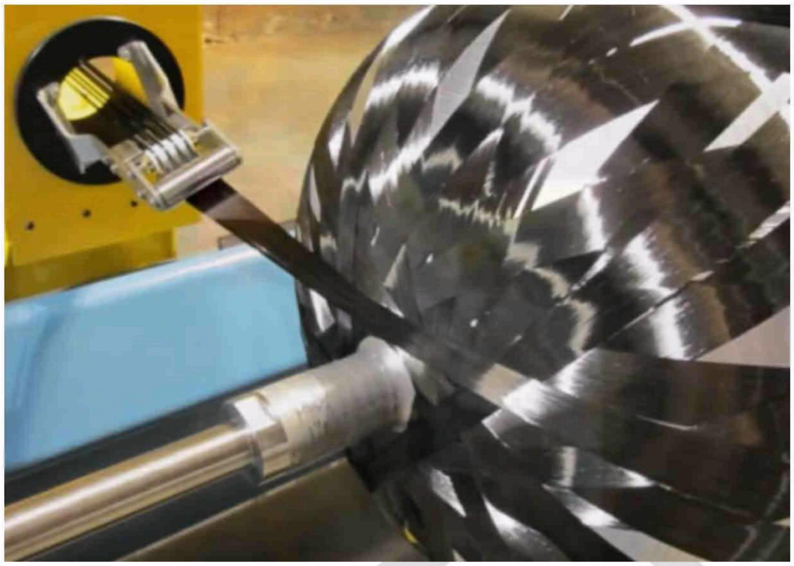

Figure 18- Step 8: Carbon Fiber Wrapping

http://www.youtube.com/watch?v=XxRiyCGtKgo

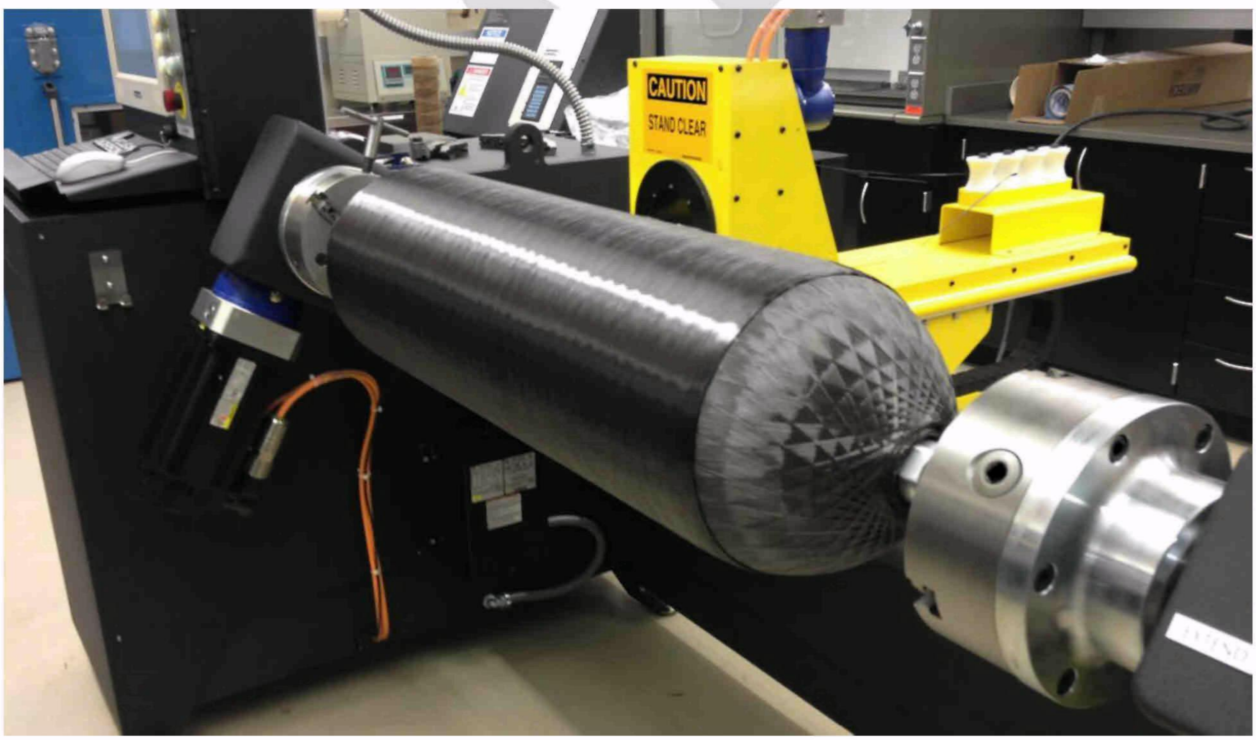

Figure 19- Step 8: Carbon Fiber Wrapping (Continued)

http://www.fleetsandfuels.com/fuels/cng/2012/11/cleanng-readies-all-new-cng-tank/attachment/cleanng_magmacel-1111

The bill of materials for the CNG Tank is shown in **Table 6**. Tank mass is 98 kg and the cost is $1,073.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**01**	**01**	**Tank Cover Sub-Subsystem**	1	**33.650**	20 01 01	
20	**01**	**02**	**Cradle Sub-Subsystem**	1	**78.280**	20 01 02	
20	**01**	**03**	**Tank Sub-Subsystem**	1	**97.959**	20 01 03	**$1,073**
20	01	03	CNG Tank	1	97.959	CIMG0098	

Table 6- BOM CNG Tank Sub-Subsystem

4. Safety Devices Subsystem

4.1. High Pressure Lock-Off Valve Sub-Subsystem

Figure 20 shows the High Pressure Lock-Off Valve directly connected to the driver's side tank end. All components included in this Sub-Subsystem are shown in **Figure 21**. The protective cover and collar were assumed die casting and sand cast respectively for high volume production. The High Pressure Lock-off Valve body was machined from billet aluminum. All components making up the HPLV were identified in the cost file with the BOM part number and the ID number assigned in **Figure 22**.

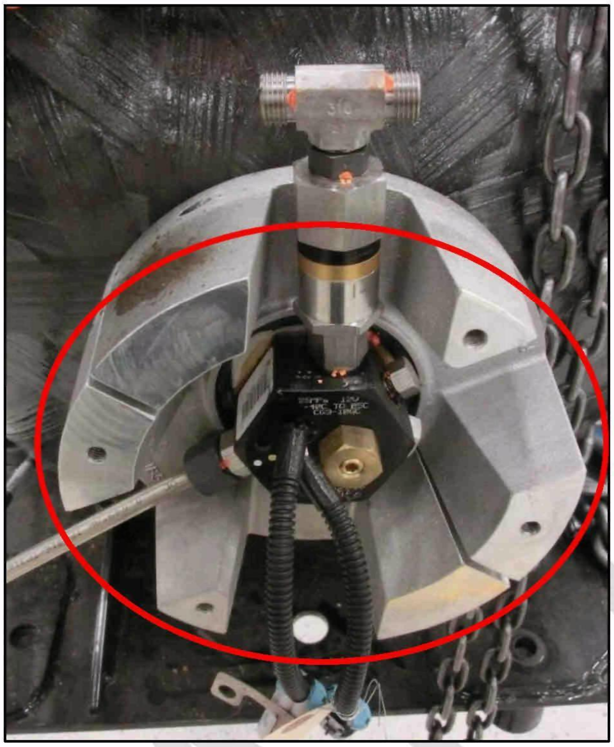

Figure 20- High Pressure Lock-Off Sub-Subsystem – Assembled

(Source: FEV, Inc. photos)

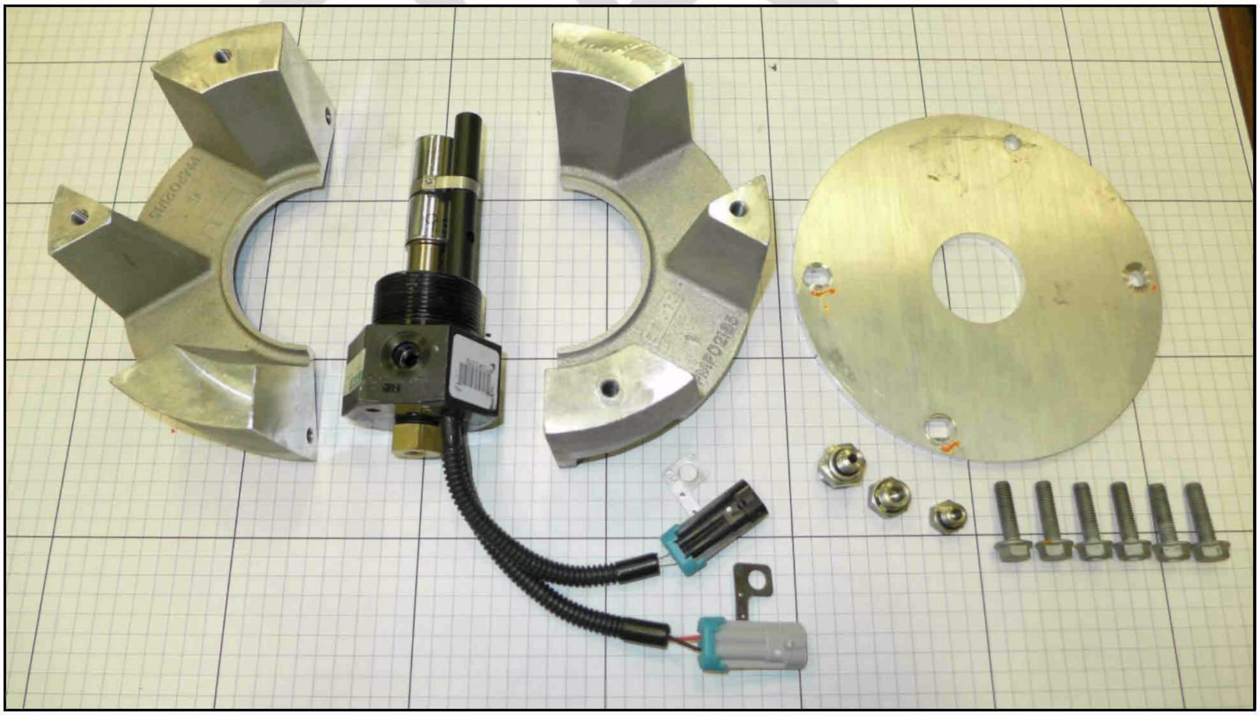

Figure 21- High Pressure Lock-Off Sub-Subsystem – Components

(Source: FEV, Inc. photos)

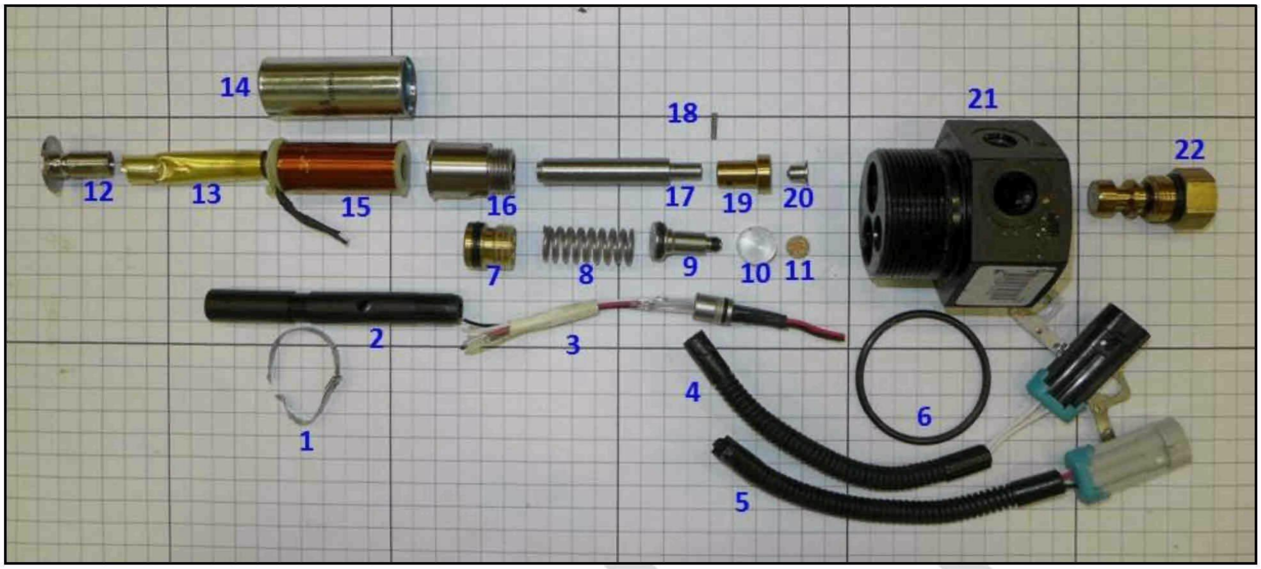

Figure 22- High Pressure Lock-Off – Exploded View

(Source: FEV, Inc. photos)

The bill of materials for the High Pressure Lock-Off Valve Sub-Subsystem is shown in **Table 7**. Mass is 3.7 kg and the cost is $55.

Part Numbering			Part Name/Description (Product Structure: System, Subsystem, Sub-Subsystem, 0 - Top Level, 1–10)	QTY	Attribute Data: Mass	Attribute Data: Photo	Cost
System	Subsystem	Sub-Subsystem		Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**02**	**01**	**High Pressure Lock-Off Valve (HPLV) Sub-Subsystem**	1	**3.676**	20 02 01	**$55**
20	02	01	Cover HLPV	1	0.469	CIMG0001	
20	02	01	Bolt, Cover HLPV	4	0.007	CIMG0002	
20	02	01	Collar, Protection, HPLV	2	2.256	CIMG0034	
20	02	01	Bolt, Collar, Protection, HLPV	2	0.036	CIMG0036	
20	02	01	P-Port Plug	1	0.015	CIMG0054	
20	02	01	I/02 Port	1	0.025	CIMG0055	
20	02	01	Line adapter, HLPV	1	0.046	CIMG0059	
20	02	01	HLPV	1	0.822	CIMG0062	

Table 7- BOM High Pressure Lock-Off Valve Sub-Subsystem

4.2. Safety Relief Valve Sub-Subsystem

Figure 23 shows the Safety Relief Valve assembled to the passenger side tank end. Separate outlets are used for both the pressure/temperature relief valve and the burst disc. Both outlets join the manual purge valve outlet before continuing to the underbody atmospheric vent.

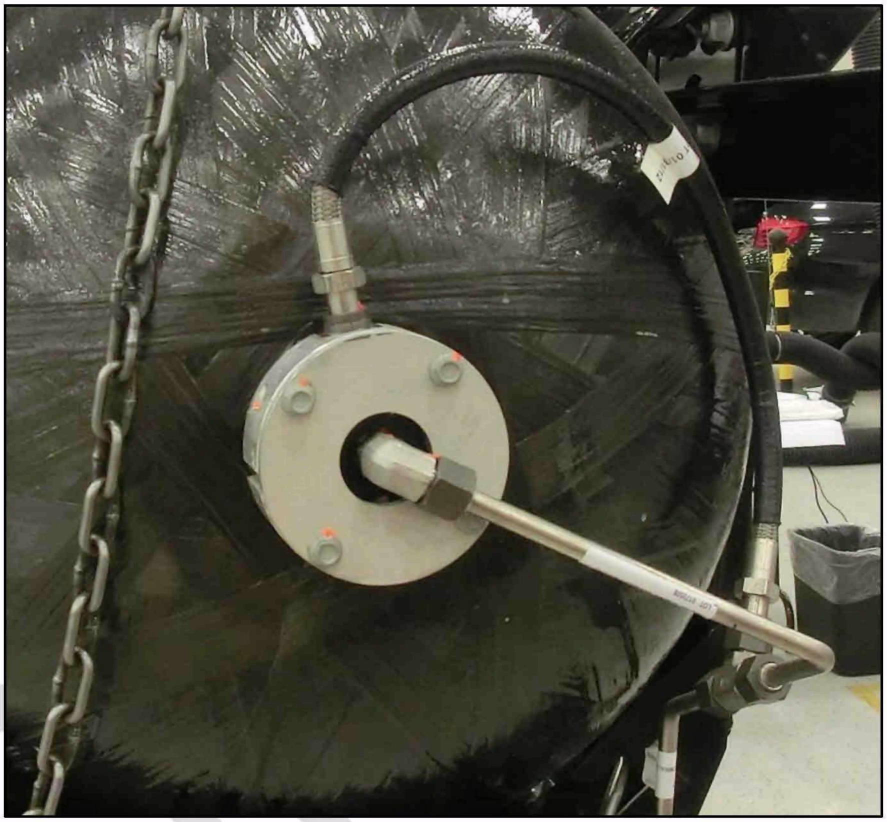

Figure 23- Safety Relief Valve – Assembled

(Source: FEV, Inc. photos)

Figure 24 identifies all components included in the Safety Relief Valve Sub-Subsystem. Unlike the protective collars of the HPLV, cross sectional thickness of the safety relief valve protective collars were able to be die cast. The protective cover was estimated as die cast as well. With exception to seals, washers, and fasteners, core components are all made from stainless steel and aluminum.

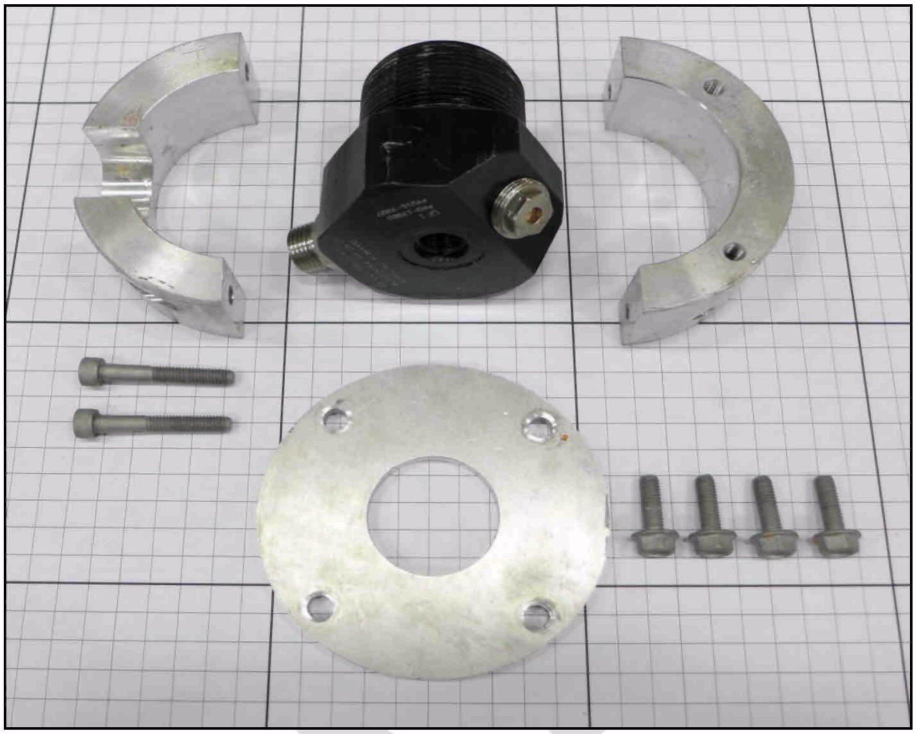

Figure 24- Safety Relief Valve – Components

(Source: FEV, Inc. photos)

Figure 25 shows the components with the pressure relief device. In the left of the picture is the over pressure relief valve assembly with belleville spring set and heat sensitive seat. The second component in from the right is the rupture disc.

Figure 25- Safety Relief Valve – Exploded View

(Source: FEV, Inc. photos)

The bill of materials for the Safety Relief Valve Sub-Subsystem is shown in **Table 8**. Mass is 1.0 kg and the cost is $26.

Part Numbering: System	Subsystem	Sub-Subsystem	Part Name/Description (Product Structure: System, Subsystem, Sub-Subsystem, 0 - Top Level, 1–10)	QTY: Quantity	Attribute Data – Mass: Total Mass (Unit Mass x qty.) "kg"	Attribute Data – Photo: Catalog Picture Reference Numbers	Cost: Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**02**	**01**	**High Pressure Lock-Off Valve (HPLV) Sub-Subsystem**	1	**3.676**	20 02 01	
20	**02**	**02**	**Safety Relief Valve Sub-Subsystem**	1	**1.004**	20 02 02	**$26**
20	02	02	Cover Plate, Relief Valve	1	0.121	CIMG0039	
20	02	02	Bolt, Cover Plate, Relief Valve	4	0.030	CIMG0040	
20	02	02	Collar, Notched, Temperature/Pressure Relief	1	0.155	CIMG0044	
20	02	02	Collar, Temperature/Pressure Relief	1	0.187	CIMG0045	
20	02	02	Bolt, Collar, Temperature/Pressure Relief	2	0.020	CIMG0045-1	
20	02	02	Relief Valve Assembly, Pressure & Temperature	1	0.491	CIMG0063	

Table 8- BOM Safety Relief Valve Sub-Subsystem

4.3. Excess Flow Valve Sub-Subsystem

Figure 26 shows the Excess Flow Valve Assembled to the High Pressure Lock-Off Valve.

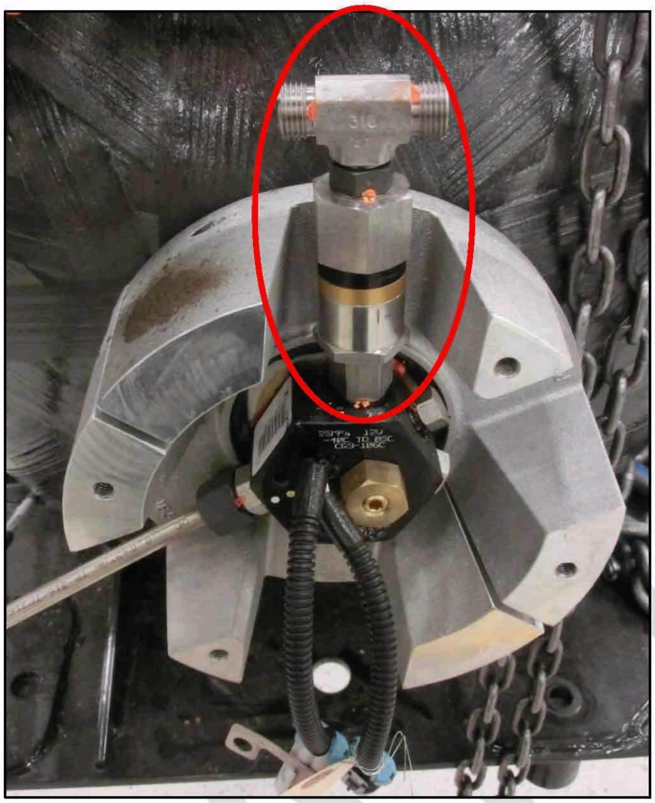

Figure 26- Excess Flow Valve – Assembled

(Source: FEV, Inc. photos)

Figure 27 shows the internal components comprising the Excess Flow Valve. All working components of this assembly are stainless steel. The spool diameters and faces are finished with grinding. The sealing surface of the mating housing are finished ground as well. The T-fitting is forged stainless steel.

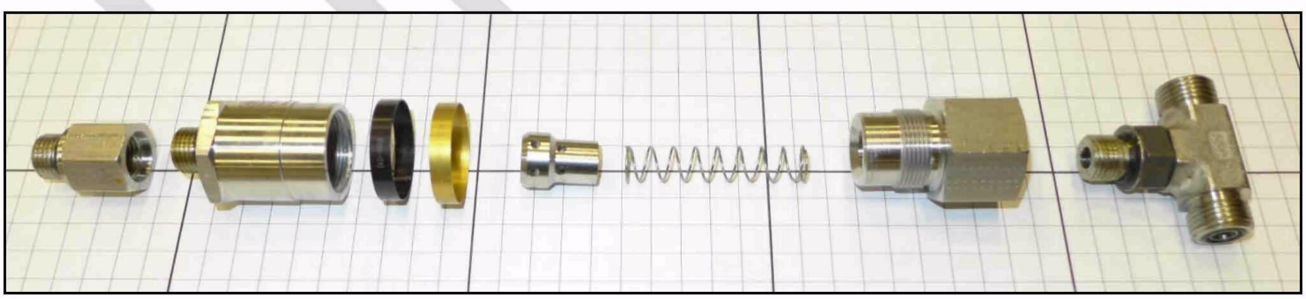

Figure 27- Excess Flow Valve – Exploded

(Source: FEV, Inc. photos)

The bill of materials for the Excess Flow Valve Sub-Subsystem is shown in **Table 9**. Mass is 0.5 kg and the cost is $23.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure (System, Subsystem, Sub-Subsystem, 0 - Top Level, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)		Mass	Photo	
System	Subsystem	Sub-Subsystem		Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**02**	**01**	**High Pressure Lock-Off Valve (HPLV) Sub-Subsystem**	1	**3.676**	20 02 01	
20	**02**	**02**	**Safety Relief Valve Sub-Subsystem**	1	**1.004**	20 02 02	
20	**02**	**03**	**Excess Flow Valve Sub-Subsystem**	1	**0.463**	20 02 03	**$23**
20	02	03	Excess Flow Valve	1	0.463	CIMG0053	

Table 9- BOM Excess Flow Valve Sub-Subsystem

4.4. Purge Sub-Subsystem

Figure 28 shows all components included in the Purge Sub-Subsystem. All fuel lines are seamless 316 stainless steel. The flex hose is stainless steel jacketed PTFE. The T and elbow fittings are forged 316 stainless steel.

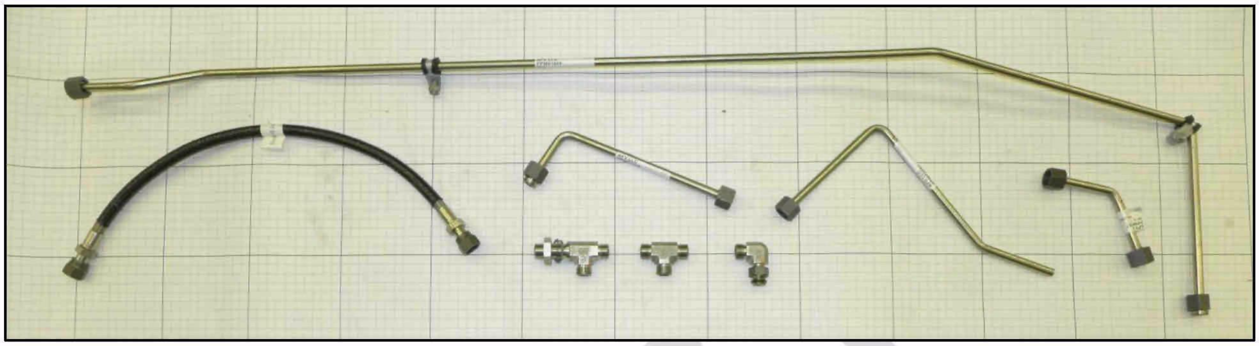

Figure 28- Purge Sub-Subsystem – Components.

(Source: FEV, Inc. photos)

The bill of materials for the Purge Sub-Subsystem is shown in **Table 10**. Mass is 1.5 kg and the cost is $47.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure: System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10		Mass	Photo	
System	Subsystem	Sub-Subsystem		Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**02**	**04**	**Purge Sub-Subsystem**	1	**1.460**	20 02 04	**$47**
20	02	04	Line, Over temperature Relief	1	0.122	CIMG0037	
20	02	04	Elbow, Over temperature Relief	1	0.102	CIMG0038	
20	02	04	Hose, Pressure Relief	1	0.256	CIMG0046	
20	02	04	Tee, Pressure/Temperature Relief	1	0.112	CIMG0047	
20	02	04	Line, Pressure Relief, Tee to Tee	1	0.093	CIMG0048	
20	02	04	Purge Line, CNG	1	0.128	CIMG0019	
20	02	04	Line, Solenoid to Purge Tee	1	0.466	CIMG0050	
20	02	04	Tee, Box, Purge	1	0.181	CIMG0061	

Table 10- BOM Purge Sub-Subsystem

5. High Pressure Circuit Subsystem

5.1. Filler (Refueling) Sub-Subsystem

Figure 29 shows all the components included in the Filler Sub-Subsystem.

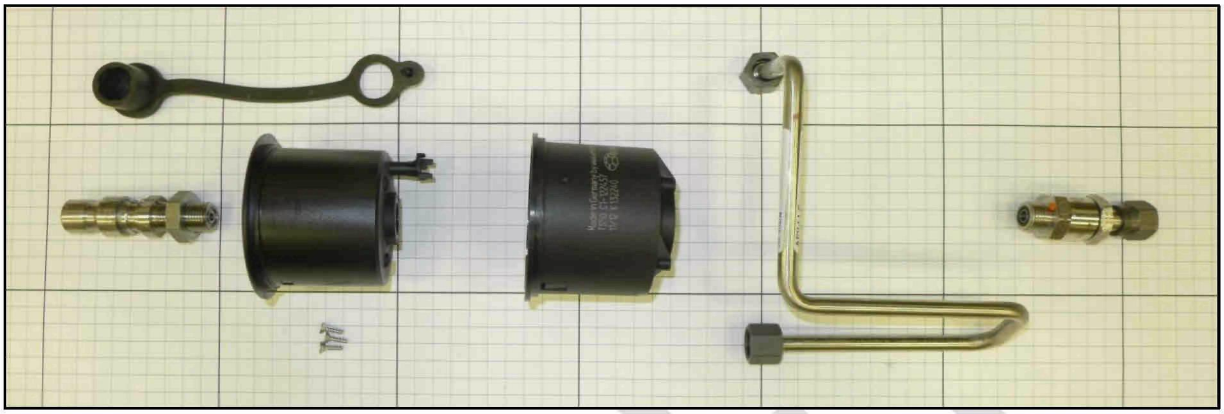

Figure 29- Filler Sub-Subsystem – Components

(Source: FEV, Inc. photos)

Figure 30 is an exploded view of the fill port (NGV1) mechanism. The body of the fill port is constructed of stainless steel. The mounting cup for the fill port is injection molded plastic.

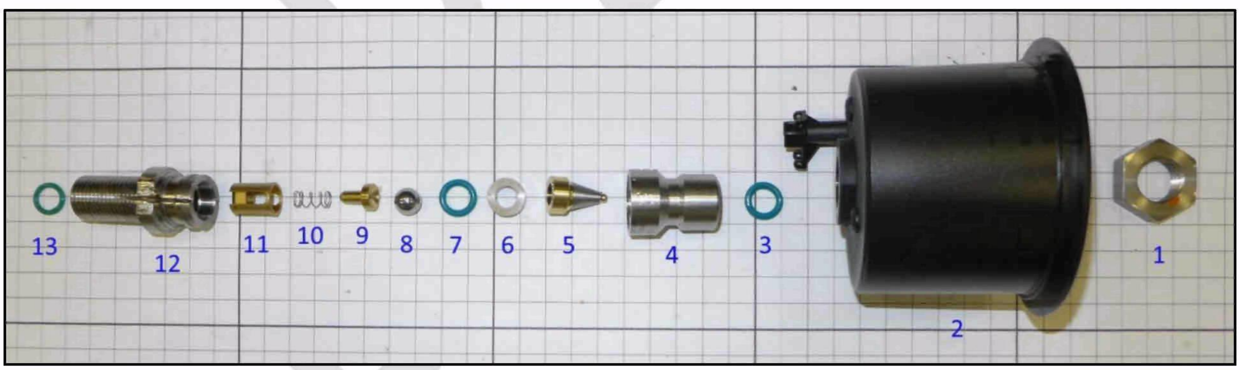

Figure 30- Fill Port – Exploded View

(Source: FEV, Inc. photos)

The bill of materials for the Filler (Refueling) Sub-Subsystem is shown in **Table 11**. Mass is 0.6 kg and the cost is $21.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**03**	**01**	**Filler (Refueling) Sub-Subsystem**	1	**0.637**	20 03 01	**$21**
20	03	01	Directional Valve, Tank Fill	1	0.146	CIMG0006	
20	03	01	Fill Port, CNG	1	0.242	CIMG0013	
20	03	01	Retainer, Fill Port, CNG	1	0.054	CIMG0014	
20	03	01	Screw, Fill Port, CNG	3	0.002	CIMG0015	
20	03	01	Fill Cap, CNG	1	0.015	CIMG0017	
20	03	01	Line, CNG, Fill to Directional Valve	1	0.178	CIMG0005	

Table 11- BOM Filler (Refueling) Sub-Subsystem

5.2. Distribution, High Pressure Sub-Subsystem

Figure 31 shows all components included in the Distribution, High Pressure Sub-Subsystem. All lines are seamless stainless steel (ASTM-213). The elbow and ball valve are stainless steel as well. Bracket costs were estimated using progressive metal stamping for high volume production.

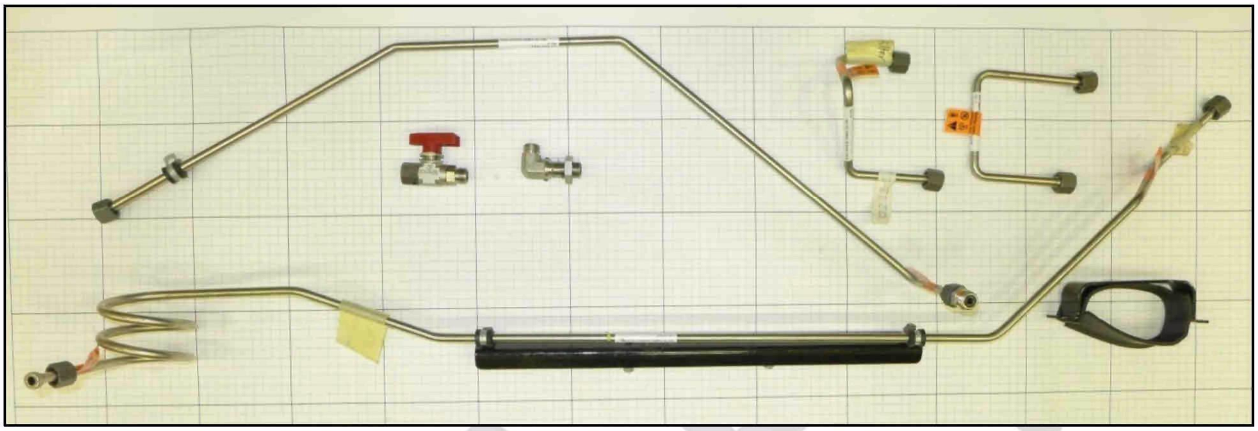

Figure 31- Distribution, High Pressure Sub-Subsystem

(Source: FEV, Inc. photos)

The bill of materials for the Distribution, High Pressure Sub-Subsystem is shown in **Table 12**. Mass is 2.4 kg and the cost is $64.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure: System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10		Mass	Photo	
System	Subsystem	Sub-Subsystem		Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**03**	**01**	**Filler (Refueling) Sub-Subsystem**	1	**0.637**	20 03 01	
20	**03**	**02**	**Distribution, High Pressure Sub-Subsystem**	1	**2.387**	20 03 02	**$64**
20	03	02	Line, CNG, Directional Valve to Shut off	1	0.140	CIMG0007	
20	03	02	Line, Solenoid to Box	1	0.388	CIMG0049	
20	03	02	Elbow, Box, Outlet	1	0.150	CIMG0060	
20	03	02	Bracket, Fuel Line, Tank to Regulator, CNG	1	0.207	CIMG0228	
20	03	02	Fuel Line, Tank to Regulator, CNG	1	1.151	CIMG0227	
20	03	02	Line, Filter to Regulator	1	0.144	CIMG0222-2	
20	03	02	Shut Off Valve, CNG	1	0.207	CIMG0018	

Table 12- BOM Distribution, High Pressure Sub-Subsystem

5.3. Filter Sub-Subsystem

Figure 32 represents the Filter Sub-Subsystem.

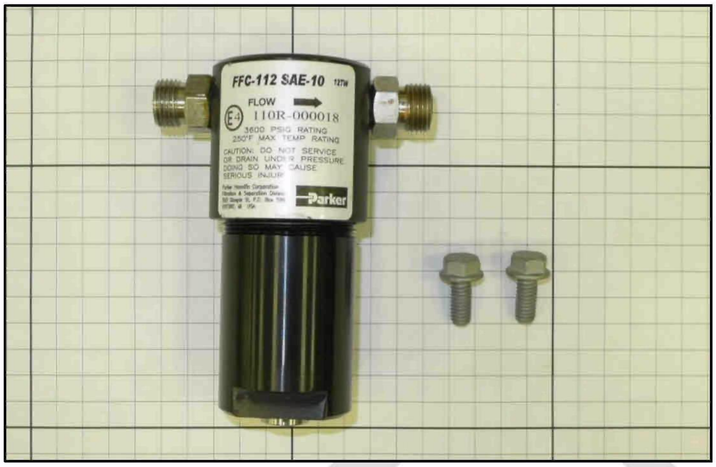

Figure 32- Filter Sub-Subsystem – Components

(Source: FEV, Inc. photos)

Figure 33 shows an exploded view of the CNG filter. The upper and lower black anodized housings are billet machined; however forging was assumed for high volume production of the pressure vessel. The filter is a 'coalescing element composed of an epoxy saturated, borosilicate glass microfiber tube surrounded by a coarse fiber drain layer retained by a synthetic fabric safety layer.' (www.parker.com) The O-rings are Buna-N and the plastic filter internal components are Acetal plastic.

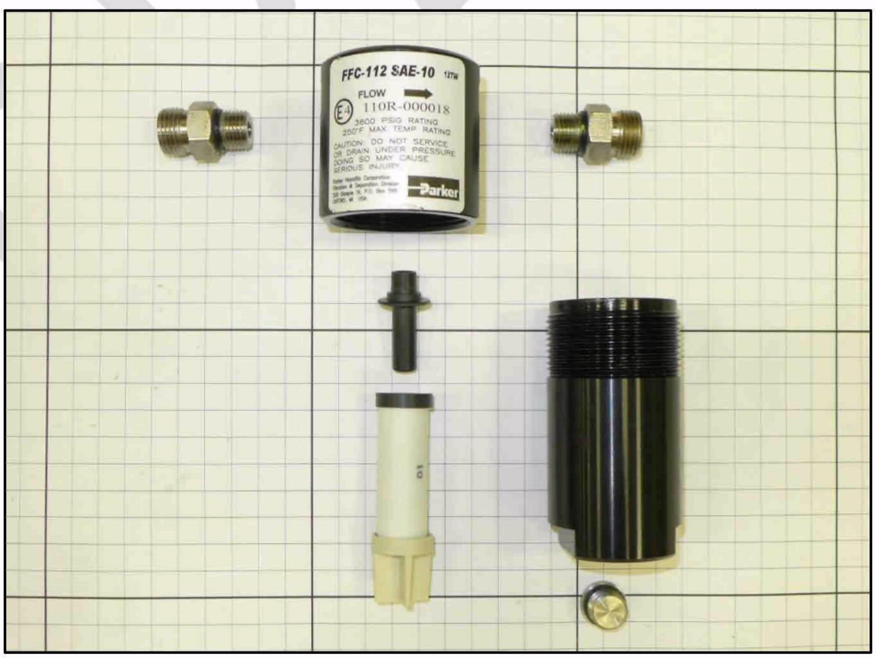

Figure 33- CNG Filter – Exploded View

(Source: FEV, Inc. photos)

The bill of materials for the Filter Sub-Subsystem is shown in **Table 13**. Mass is 0.6 kg and the cost is $18.

Part Numbering: System	Subsystem	Sub-Subsystem	Part Name/Description (Product Structure)	QTY: Quantity	Attribute Data – Mass: Total Mass (Unit Mass x qty.) "kg"	Attribute Data – Photo: Catalog Picture Reference Numbers	Cost: Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**03**	**01**	**Filler (Refueling) Sub-Subsystem**	1	**0.637**	20 03 01	
20	**03**	**02**	**Distribution, High Pressure Sub-Subsystem**	1	**2.387**	20 03 02	
20	**03**	**03**	**Filter Sub-Subsystem**	1	**0.613**	20 03 03	**$21**
20	03	03	Filter	1	0.613	CIMG0223	
20	03	03	Bolt, Filter	2	0.030	CIMG0224	

Table 13- BOM Filter Sub-Subsystem

5.4. Pressure Regulator Sub-Subsystem

Figure 34 shows all the components included in the Pressure Regulator Sub-Subsystem including the bracket, guard, fasteners, regulator, and ground strap.

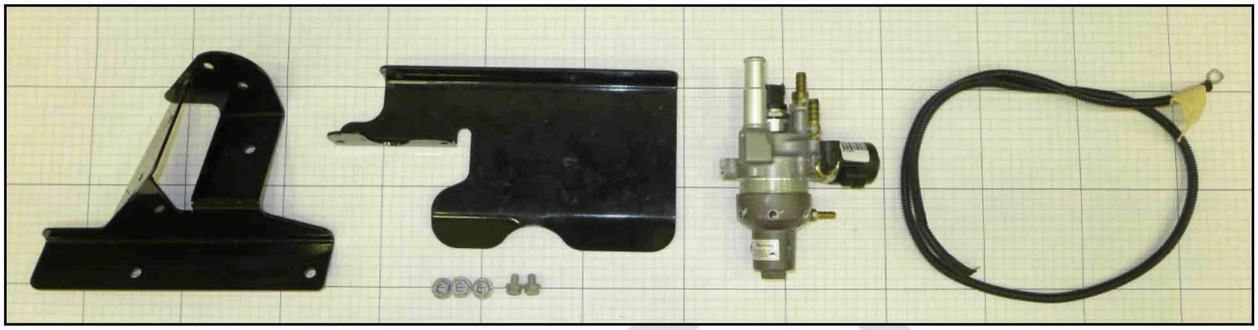

Figure 34- Pressure Regulator Sub-Subsystem – Components

(Source: FEV, Inc. photos)

Figure 35 shows an exploded view of the CNG regulator. The unit produced by GFI is a single stage regulator. It features coolant heating, integral high pressure solenoid shut-off, pressure and temperature transmitters. The upper and lower housings are both die cast. A variety of manufacturing processes are used in creating the internals including wire forming, machining, injection molding and stamping. Cost considerations were made for stringent cleanliness requirements needed for this application.

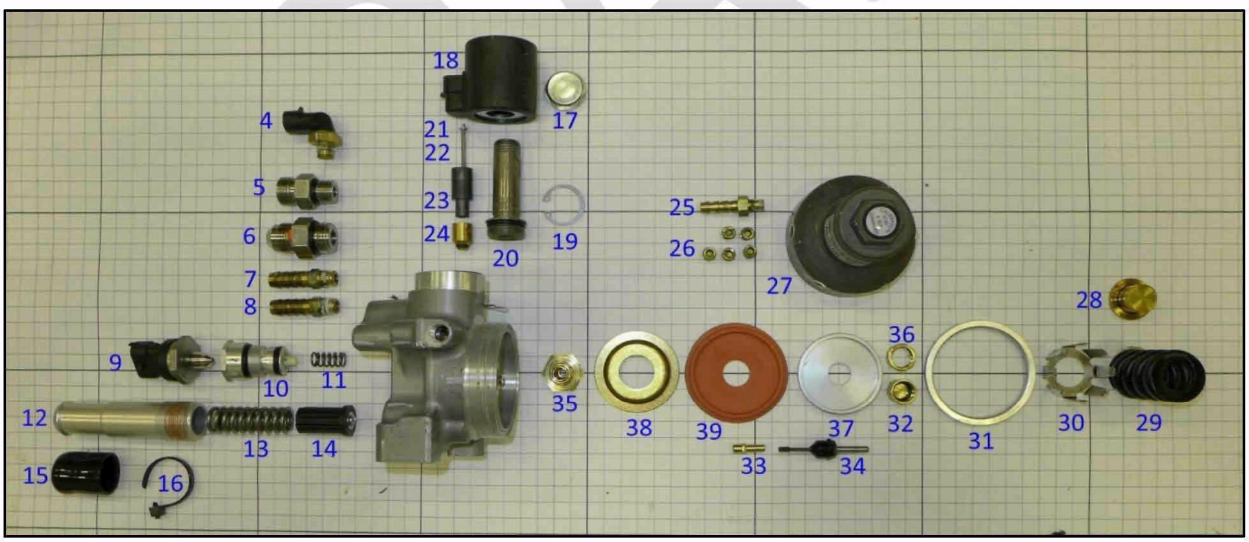

Figure 35- Pressure Regulator – Exploded View

(Source: FEV, Inc. photos)

The bill of materials for the Pressure Regulator Sub-Subsystem is shown in **Table 14**. Mass is 4.1 kg and the cost is $78.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**03**	**01**	**Filler (Refueling) Sub-Subsystem**	1	**0.637**	20 03 01	
20	**03**	**02**	**Distribution, High Pressure Sub-Subsystem**	1	**2.387**	20 03 02	
20	**03**	**03**	**Filter Sub-Subsystem**	1	**0.613**	20 03 03	
20	**03**	**04**	**Pressure Regulator Sub-Subsystem**	1	**4.095**	20 03 04	**$78**
20	03	04	Ground Strap, CNG Regulator	1	0.061	CIMG0221	
20	03	04	Regulator Assembly, CNG	1	1.480	CIMG0222-3	
20	03	04	Fasteners, Regulator Assembly, CNG	2	0.027	CIMG0225	
20	03	04	Bracket, Regulator, CNG	1	1.184	CIMG0238	
20	03	04	Guard, Regulator, CNG	1	1.306	CIMG0239	
20	03	04	Nuts, CNG Regulator Bracket	3	0.037	CIMG0240	

Table 14- BOM Pressure Regulator Sub-Subsystem

6. Low Pressure Circuit Subsystem

6.1. Distribution, Low Pressure Sub-Subsystem

Figure 36 shows all components included in the Low Pressure Distribution Sub-Subsystem including the brackets used for line mounting. Lines used for CNG transport are either stainless steel or braided stainless steel reinforced flex lines. Coolant transfer hoses for the pressure regulator heating circuit are SAE20R3 and the regulator vacuum reference hoses are SAE30R7.

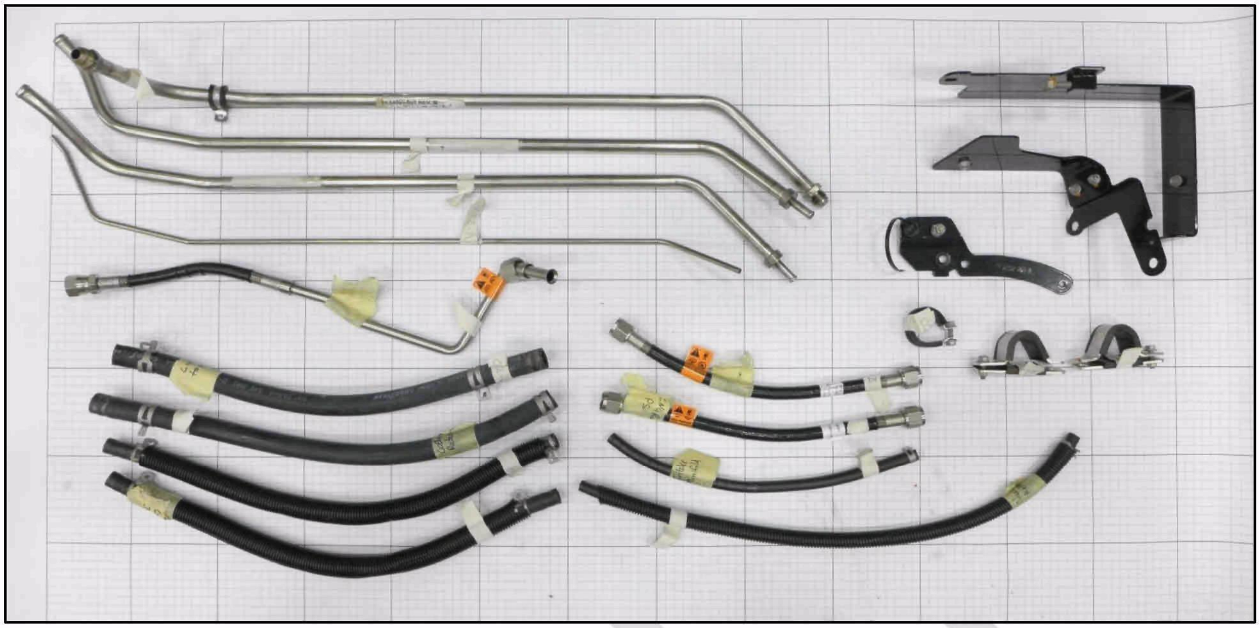

Figure 36- Distribution, Low Pressure Sub-Subsystem – Components

(Source: FEV, Inc. photos)

The bill of materials for the Distribution, Low Pressure Sub-Subsystem is shown in **Table 15**. Mass is 4.6 kg and the cost is $109.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
System	Subsystem	Sub-Subsystem	Product Structure: System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Mass: Total Mass (Unit Mass x qty.) "kg"	Photo: Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**04**	**00**	**Low Pressure Circuit Subsystem**	1	**8.622**		
20	**04**	**01**	**Distribution, Low Pressure Sub-Subsystem**	1	**4.621**	20 04 01	**$109**
20	04	01	Line Cluster, CNG Regulator	1	3.027	CIMG0202	
20	04	01	Bracket, Rear, Line Cluster, CNG Regulator	1	0.396	CIMG0250	
20	04	01	Bracket, Mid, Line Cluster, CNG Regulator	1	0.721	CIMG0251	
20	04	01	Bracket, Front, Line Cluster, CNG Regulator	1	0.177	CIMG0252	
20	04	01	Line, Regulator to Fuel Rail	1	0.300	CIMG0222-1	

Table 15- BOM Distribution, Low Pressure Sub-Subsystem

6.2. Fuel Rails Sub-Subsystem

Figure 37 shows the Fuel Rail Sub-Subsystem partially disassembled. The fuel injector has been removed from the assembly to be included in its own sub-system. The wide upper rail shown in the top center of the image supplies the fuel injector. The lower rail shown center right of image is a shorter rail that is fed from the injector. The CNG flow path then travels through a barbed fitting to a rubber hose and finally to an intake manifold mounted nozzle shown in **Figure 38**. The nozzle is a straight thru diameter with no specialized geometry.

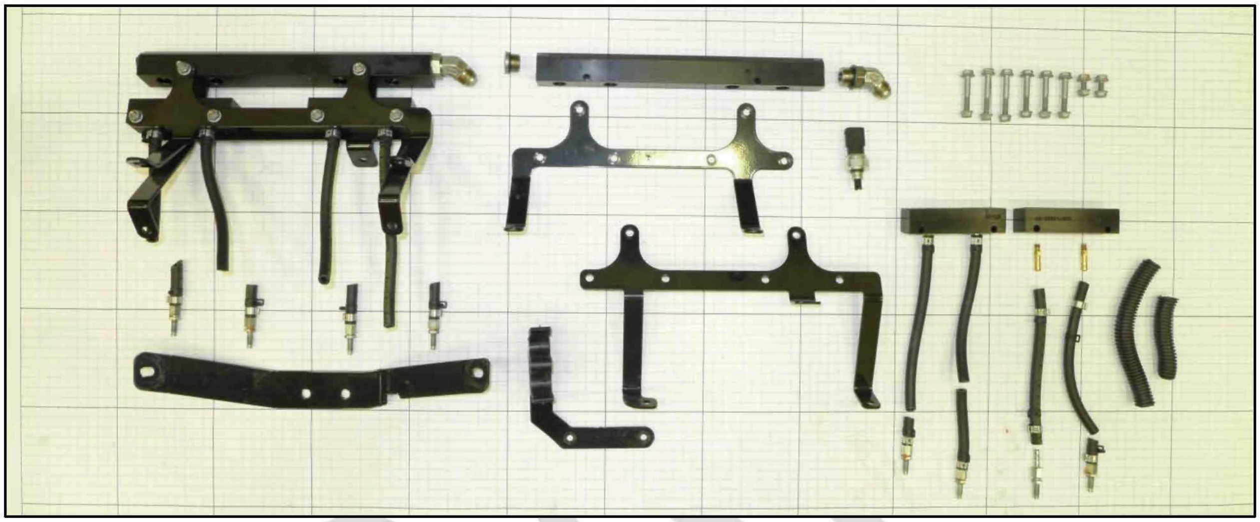

Figure 37- Fuel Rails Sub-Subsystem – Components

(Source: FEV, Inc. photos)

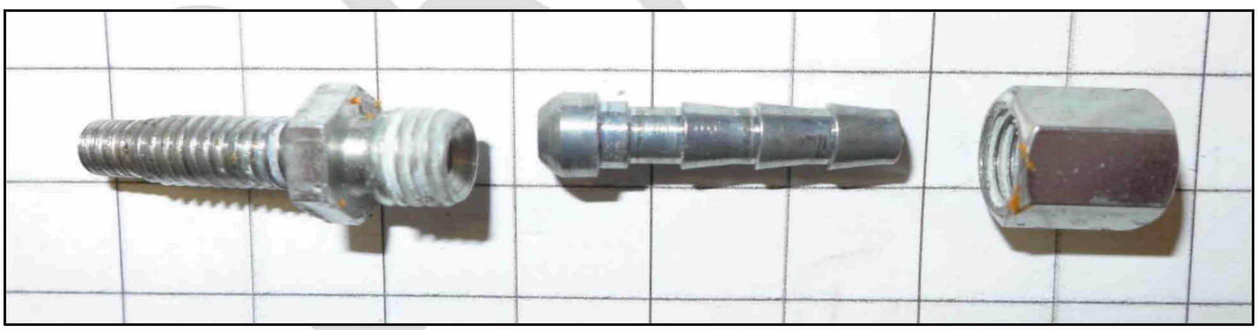

Figure 38- Injector Nozzle – Components

(Source: FEV, Inc. photos)

The bill of materials for the Fuel Rail Sub-Subsystem is shown in **Table 16**. Mass is 3.8 kg and the cost is $74.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**04**	**00**	**Low Pressure Circuit Subsystem**	1	**8.622**		
20	**04**	**01**	**Distribution, Low Pressure Sub-Subsystem**	1	**4.621**	20 04 01	
20	**04**	**02**	**Fuel Rails Sub-Subsystem**	1	**3.825**	20 04 02	**$74**
20	04	02	Bolt, Fuel Rail, CNG	1	0.077	CIMG0215	
20	04	02	Fuel Rail Assembly, CNG	1	3.748	CIMG0216	

Table 16- BOM Fuel Rails Sub-Subsystem

6.3. Fuel Injector Sub-Subsystem

Figure 39 shows all components included in the Fuel Injector Sub-Subsystem. One (1) CNG injector is used for each cylinder.

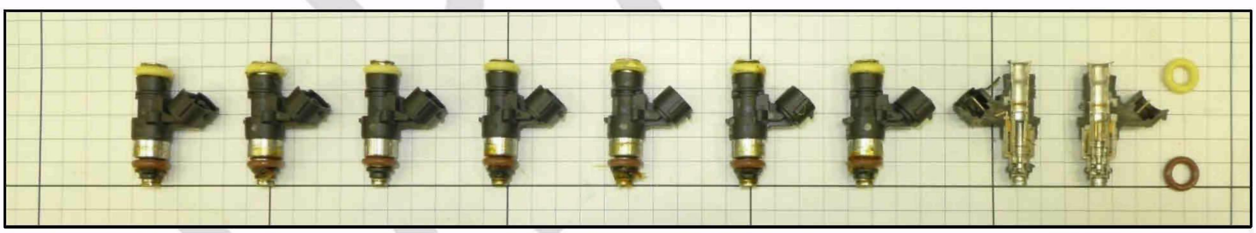

Figure 39- Fuel Injector Sub-Subsystem – Components

(Source: FEV, Inc. photos)

CNG rail pressure is 90-110 psig. In comparison, gasoline fuel injector rail pressure is approximately 55 psig. Lower energy density of CNG requires a higher flow rate. The construction of the CNG injector is very similar to a gasoline injector with a cost premium for non-lubricated fuel operation. **Figure 40** shows a cross section of the CNG injector.

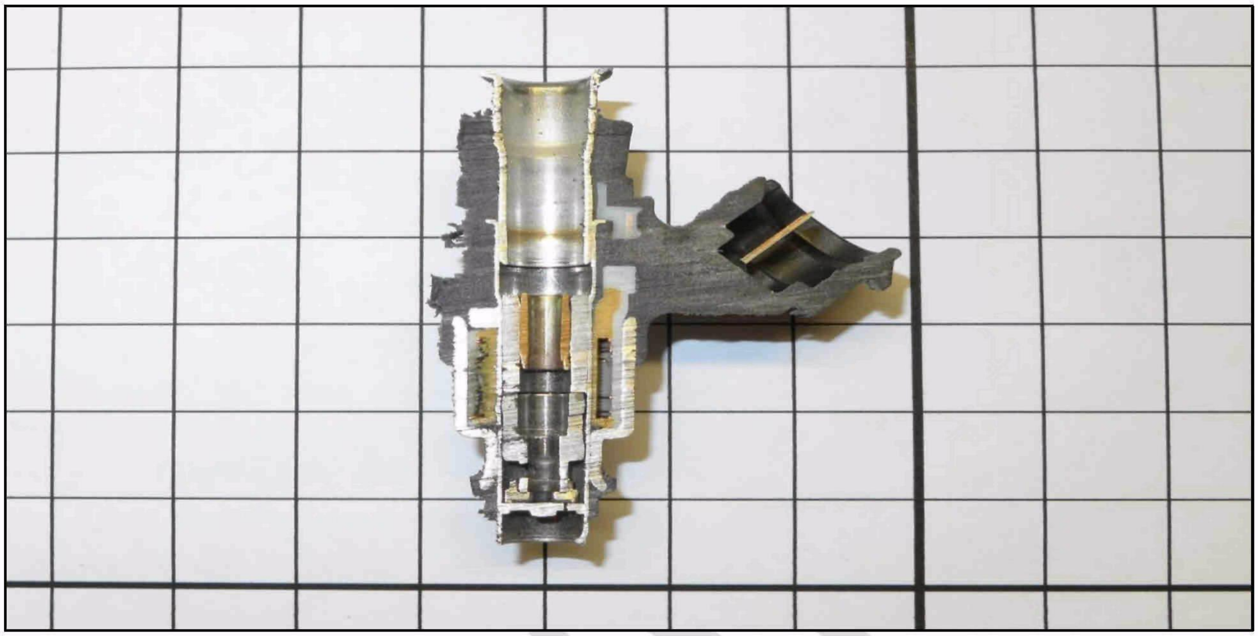

Figure 40- CNG Fuel Injector – Sectioned

(Source: FEV, Inc. photos)

The bill of materials for the Fuel Injectors Sub-Subsystem is shown in **Table 17**. Mass is 0.2 kg and the cost is $95.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**04**	**00**	**Low Pressure Circuit Subsystem**	1	**8.622**		
20	**04**	**01**	**Distribution, Low Pressure Sub-Subsystem**	1	**4.621**	20 04 01	
20	**04**	**02**	**Fuel Rails Sub-Subsystem**	1	**3.825**	20 04 02	
20	**04**	**03**	**Fuel Injectors Sub-Subsystem**	8	**0.176**	CIMG0216-7	**$95**
20	04	03	Fuel Injector	8	0.176	CIMG0216-7	

Table 17- BOM Fuel Injectors Sub-Subsystem

7. Controls Subsystem

7.1. Control Module Sub-Subsystem

All components associated with the Control Module Sub-Subsystem are identified in **Figure 41**. From left to right are the ECU mounting bracket, ECU, Intake Air Temperature module and Fuel Pump module. The Silverado CNG system utilizes a separate ECU.

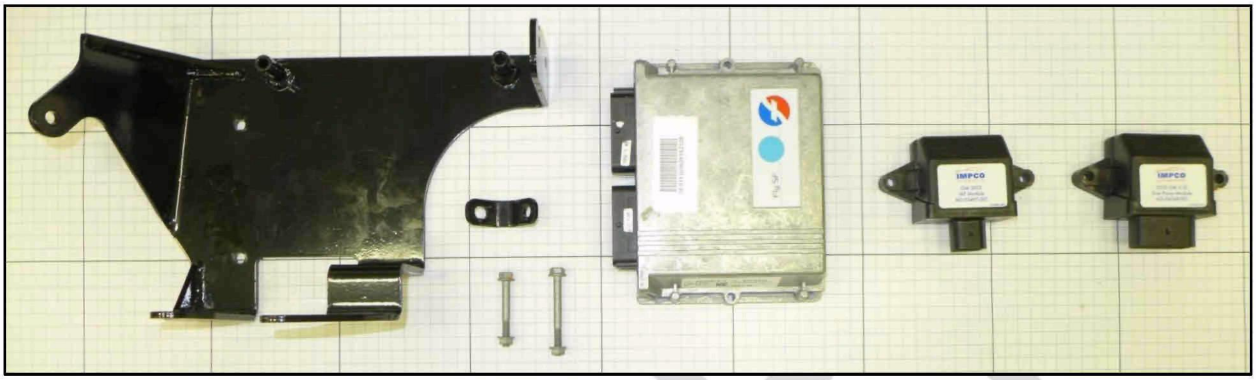

Figure 41- Control Module Sub-Subsystem – Components

(Source: FEV, Inc. photos)

Figure 42 shows the interior of the CNG ECU including both die cast covers, seal, board and fasteners.

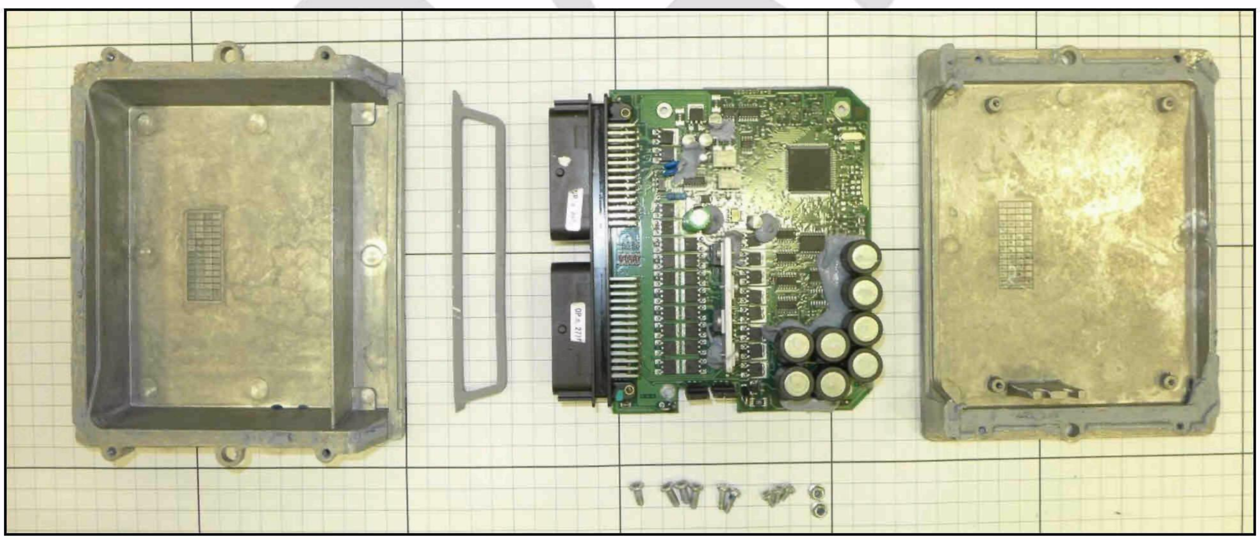

Figure 42- CNG ECU – Exploded View

(Source: FEV, Inc. photos)

ECU circuitry was reviewed in detail. Each board component was identified and costed individually including assembly cost. **Figure 43** and **Figure 44** show top and bottom views of ECU board with number labels matching the table with circuit description.

ID	ECU (Top)	Quantity
1	Aluminum Capacitor- TMD	8
2	Aluminum Capacitor- TMD	1
3	Transistor- TMD	2
4	IC 4 pin- SMD	10
5	IC 4 pin- SMD	8
6	IC 4 pin- SMD	8
7	Diode- TMD	2
8	IC 14 Pin- SMD	4
9	IC 18 Pin- SMD	1
10	IC 8 Pin- SMD	3
11	Transistor / Voltage Regulator IC- TMD	2
12	Transistor / Voltage Regulator IC- TMD	2
13	Glass Diode- SMD	9
14	Resistor- TMD	1
15	Aluminum Capacitor- SMD	1
16	Aluminum Capacitor- SMD	2
17	Aluminum Capacitor- SMD	1
18	Aluminum Capacitor- SMD	1
19	Capacitor- TMD	2
20	IC 3 Pin- SMD	17
21	Diode 2 Pin- SMD	1
22	IC 4 pin- SMD	2
23	IC 2 Pin- SMD	1
24	IC 16 Pin- SMD	1
25	IC 4 pin- SMD	1
26	IC 4 pin- SMD	2
27	Relay 8 Pin- SMD	2
28	IC 14 Pin- SMD	1
29	Crystal 4 pin- SMD	1
30	Resistor- SMD	1
31	Resistor- SMD	5
32	Resistor- SMD	23
33	Resistor 8 Pin- SMD	3
34	Capacitor- SMD	17
35	CPU	1
36	Board Connector	
37	Circuit Board	

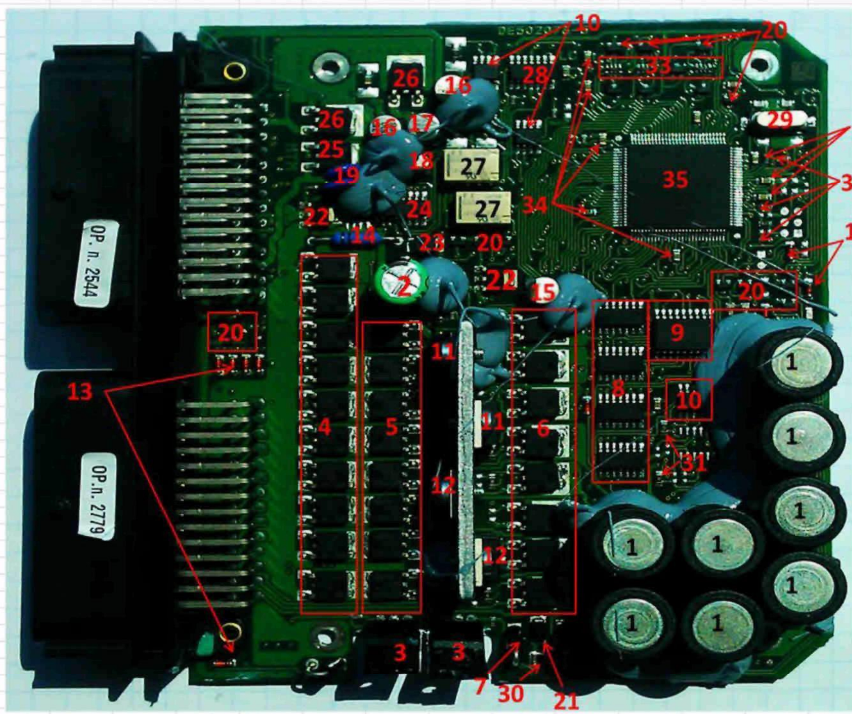

Figure 43- CNG ECU Board with Circuit ID numbers – Top

(Source: FEV, Inc. photos)

ECU Control Board (Bottom)

ID	ECU (Bottom)	Quantity
1	Diode 2 Pin- SMD	36
2	Glass Diode- SMD	49
3	Resistor- SMD	8
4	Resistor- SMD	16
5	Resistor- SMD	46
6	Resistor- SMD	150
7	Capacitor- SMD	131
8	IC 3 Pin- SMD	20
9	Diode 2 Pin- SMD	1

Figure 44- CNG ECU Board with Circuit ID numbers – Bottom

(Source: FEV, Inc. photos)

The bill of materials for the Control Module Sub-Subsystem is shown in **Table 18**. Mass is 3.7 kg and the cost is $232.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**04**	**00**	**Low Pressure Circuit Subsystem**	1	**8.622**		
20	**05**	**00**	**Controls Subsystem**	1	**6.488**		
20	**05**	**01**	**Control Module Sub-Subsystem**	1	**3.688**	20 05 01	**$232**
20	05	01	ECU, CNG	1	0.917	CIMG0088	
20	05	01	Bracket, CNG Controller	1	2.210	CIMG0141-1	
20	05	01	Fasteners, ECU & CNG controller bracket	1	0.054	CIMG0141-3	
20	05	01	Fuel Pump Module, CNG	1	0.273	CIMG0236	
20	05	01	Intake Air Tempurature (IAT) Module	1	0.234	CIMG0141-2	

Table 18- BOM Control Module Sub-Subsystem

7.2. Wire Harnesses Sub-Subsystem

Figure 45 shows the components comprising the Wire Harness Sub-Subsystem, main harness shown left and rearward harness shown right. Both harnesses are dedicated to the CNG system. The main harness connects the ECU, IAT module, regulator and injectors. The rear harness connects the main harness, fuel pump, fuel pump module, as well as high pressure safety lock off connections.

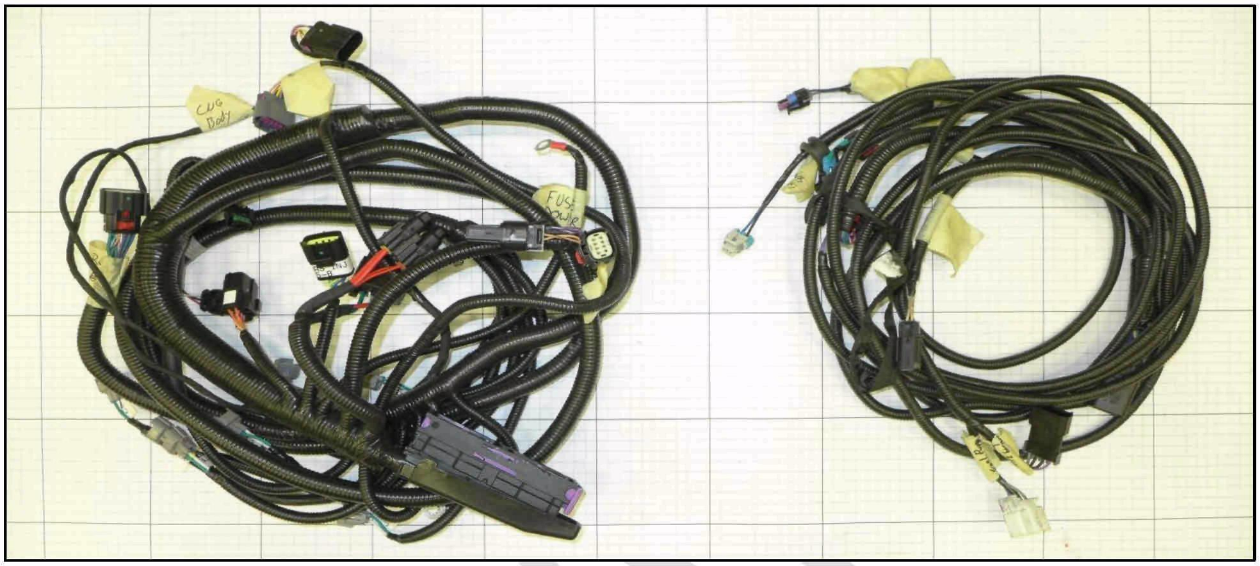

Figure 45- Wire Harness Sub-Subsystem

The bill of materials for the Wire Harnesses Sub-Subsystem is shown in **Table 19**. Mass is 2.8 kg and the cost is $71.

Part Numbering			Part Name/Description	QTY	Attribute Data		Cost
			Product Structure		Mass	Photo	
System	Subsystem	Sub-Subsystem	System / Subsystem / Sub-Subsystem / 0 - Top Level / 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10	Quantity	Total Mass (Unit Mass x qty.) "kg"	Catalog Picture Reference Numbers	Unit Cost
20	**00**	**00**	**Compressed Natural Gas System**		**239.334**		
20	**01**	**00**	**Storage Subsystem**	1	**209.889**	20 01	
20	**02**	**00**	**Safety Devices Subsystem**	1	**6.603**		
20	**03**	**00**	**High Pressure Circuit Subsystem**	1	**7.732**		
20	**04**	**00**	**Low Pressure Circuit Subsystem**	1	**8.622**		
20	**05**	**00**	**Controls Subsystem**	1	**6.488**		
20	**05**	**01**	**Control Module Sub-Subsystem**	1	**3.688**	20 05 01	
20	**05**	**02**	**Wire Harnesses Sub-Subsystem**	1	**2.800**	20 05 02	**$71**
20	05	02	Wire Harness, CNG System	1	2.091	CIMG0217	
20	05	02	Wire Harness, CNG Rear	1	0.709	CIMG0241	

Table 19- BOM Wire Harnesses Sub-Subsystem

8. Cost Summary and Conclusion

The primary project objective was to determine net incremental direct manufacturing costs (NIDMC) for a complete Compressed Natural Gas (CNG) fuel system. The system selected to represent the light-duty pickup truck segment was a 2013 Chevrolet Silverado equipped with the bi-fuel option. A NIDMC of $2,276 (**Table 20)** represents the calculated cost to the OEM to add a CNG fuel system to an existing gasoline vehicle. The boundary conditions for the cost analysis included manufacturing in the United States, high production volume, and a mature and competitive market place. Not included in the NIDMC are OEM indirect costs such as corporate overhead, research and develop, and tooling (incremental tooling provide separately in Appendix A). In addition, there is no OEM profit included in the calculation. Both OEM indirect costs and profit are added to the FEV calculated NIDMC using an EPA Indirect Cost Multiplier (ICM). The application of the multiplier was outside the scope of this project.

Table 20 - CNG Subsystem Cost Summary Overview

Subsystem	Total Direct Manufacturing (i.e., material, labor and manufacturing overhead)	Total Markup Cost (i.e., end item scrap, SG&A, Profit, ED&T/R&D)	Total Packaging Cost	Net Incremental Direct Manufacturing Cost
Storage	$1,175	$177	$9	$1,360
Safety Devices	$126	$24	$1	$151
High Pressure Circuit	$154	$28	$3	$184
Low Pressure Circuit	$268	$38	$2	$278
Controls	$268	$35	$1	$303
TOTAL	**$1,959**	**$302**	**$15**	**$2,276**

Additional cost details for each subsystem listed in **Table 20** can be found in **Appendix A**. As highlighted in **Figure 46**, the largest contributor to the overall CNG system cost is the storage system at 60% of the total NIDMC.

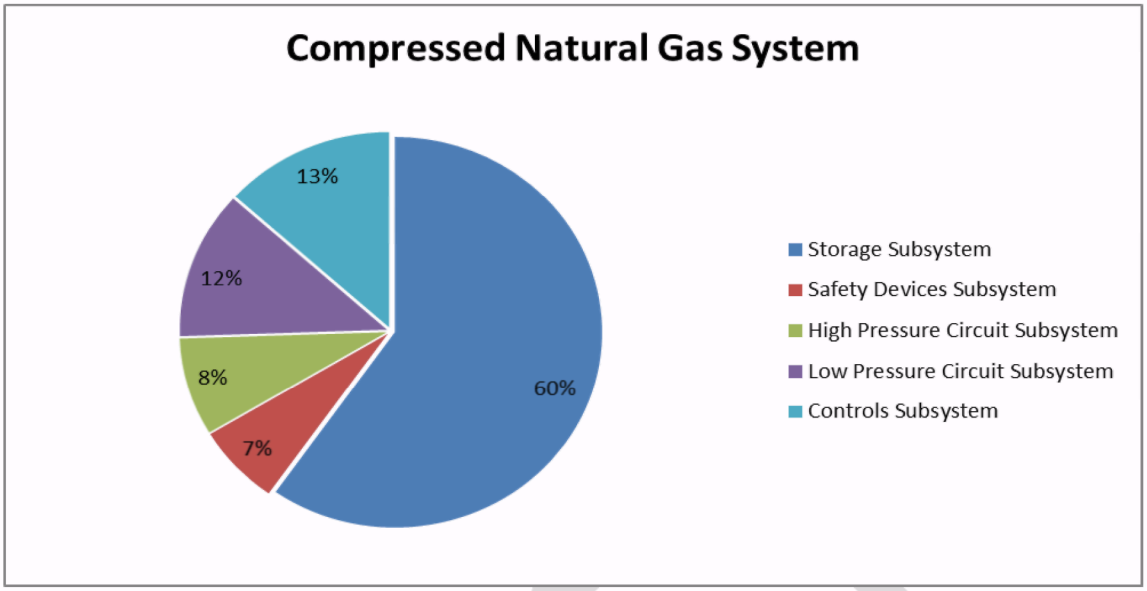

Figure 46- CNG Subsystems

Material cost makes up $1531.20 of the total $2276.20 for the CNG system, most of which comes from the carbon-fiber wrapped fuel tank. See **Figure 47** for a detailed breakdown.

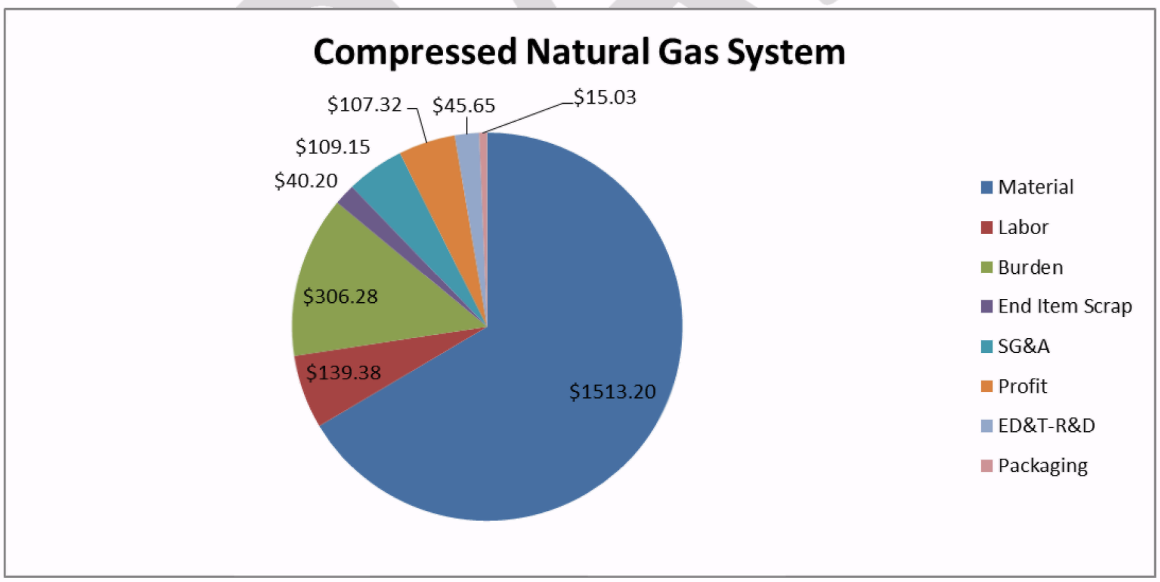

Figure 47- Manufacturing and Mark-up Cost

All costs were developed using a volume assumption of 450,000 units per year. This cost analysis is inclusive of all associated assembly cost from component to vehicle. Calculations were performed to determine equipment sizing, cycle times and material usage requirements. FEV utilized its extensive database of rates for equipment, labor, material, end item scrap, selling, general and administrative (SG&A), profit, and engineering, design and testing (ED&T) to develop costs representative of what an OEM would incur for such a system in high volume automotive manufacturing.

Costs were developed for all critical components by detailing each operation in a Manufacturing Assumptions Quote Sheet (MAQS). Process calculators were used to determine equipment size and corresponding rate ($/hr), cycle time (seconds) and material usage (kg). For example, the Pressure Regulator Cap was identified as an aluminum die casting. The number of slide pulls, cavities, part width, part height, average wall thickness, parting line area, cavity surface area, and max wall thickness were all used to determine the die-casting machine size, cycle time and material usage. This information was then transferred to the MAQS where rates are pulled in for material, labor, manufacturing overhead/burden, end item scrap, SG&A, profit, and ED&T. Cost contributions are then calculated for these core cost elements. Similar process calculators are used for subsequent processing such as machining, where all machine features are measured, speed and feed rates assigned based on the respective material, and feed times calculated. In addition pallet changes, tool changes, rapid times, as well as estimated work pieces per fixture are used to estimate the total cycle time. Finally all processes are summed, end item packaging estimated, and total cost calculated. Cost contributions for the core cost elements are then linked to the Cost Model Analysis Template (CMAT). The CMAT incorporates cost data from various Sub-Subsystems into one summary sheet. For detailed cost breakdown, see **Appendix A**.

Overall system costing methods are either calculated or commodity. All fastening hardware (bolts, washers, nuts, etc...) come from online bolt manufacturer’s pricing. Commodity pricing was also used on small components within larger assemblies such as the ECU circuits and components within assemblies like the pressure regulator. For example commodity pricing was referenced to estimate costs for components like springs, seals, solenoids, and diaphragms.

9. Appendix A

The CNG system level cost summary, by major components and assemblies, is shown below in **Table 21**.

Table 21 - Complete Cost Summary (CMAT) – CNG System

BASE TECHNOLOGY GENERAL PART INFORMATION								BASE TECHNOLOGY PACKAGE COST INFORMATION												
Item	System	Subsystem	Sub-Subsystem	Assembly	Subassembly	Component	Name/Description	Manufacturing			Total Manufacturing Cost (Component/ Assembly)	Markup				Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component / Assembly)	Net Component/ Assembly Cost Impact to OEM	Tooling (x1000)	Investment (X1000)
								Material	Labor	Burden		End Item Scrap	SG&A	Profit	ED&T-R&D					
								USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
	20						Compressed Natural Gas System	-	-	-	-	-	-	-	-	-	-	-	-	-
1		01					Storage Subsystem	978.16	53.04	143.33	1,174.53	35.11	61.97	58.03	21.86	176.98	8.84	1,360.35	5,242,012.93	5,242,012.93
			01				Tank Cover Sub-Subsystem	70.61	3.51	4.13	78.25	0.46	6.52	5.62	1.33	13.92	1.33	93.50	1,990,310.80	1,990,310.80
			02				Cradle Sub-Subsystem	134.40	11.74	11.10	157.24	1.19	13.80	13.97	4.51	33.47	2.65	193.37	2,591,702.13	2,591,702.13
			03				Tank Sub-Subsystem	773.15	37.79	128.10	939.04	33.46	41.65	38.45	16.02	129.58	4.86	1,073.48	660,000.00	660,000.00
2		02					Safety Devices Subsystem	73.53	17.06	35.14	125.72	1.27	9.47	9.25	4.31	24.29	0.52	150.54	5,388,063.40	5,388,063.40
			01				High Pressure Lock-Off Valve Sub-Subsystem	19.81	6.75	17.60	44.15	0.73	3.79	3.93	2.11	10.56	0.24	54.95	2,948,929.80	2,948,929.80
			02				Safety Relief Valve Sub-Subsystem	7.35	4.40	9.28	21.03	0.25	1.73	1.83	1.00	4.81	0.16	25.99	2,403,133.60	2,403,133.60
			03				Excess Flow Valve Sub-Subsystem	9.13	3.98	5.96	19.07	0.11	1.51	1.37	0.45	3.45	0.06	22.59	36,000.00	36,000.00
			04				Purge Sub-Subsystem	37.25	1.93	2.29	41.47	0.17	2.43	2.12	0.75	5.47	0.06	47.01	-	-
3		03					High Pressure Circuit Subsystem	99.36	21.38	33.13	153.87	1.22	11.01	11.17	4.25	27.65	2.75	184.27	4,010,710.40	4,010,710.40
			01				Filler (Refueling) Sub-Subsystem	5.12	5.54	6.86	17.52	0.10	1.44	1.23	0.29	3.05	0.26	20.83	330,386.80	330,386.80
			02				Distribution, High Pressure Sub-Subsystem	46.40	3.23	3.78	53.42	0.30	3.49	3.56	1.47	8.83	1.97	64.22	248,695.00	248,695.00
			03				Filter Sub-Subsystem	6.81	3.65	7.10	17.55	0.23	1.29	1.14	0.35	3.01	0.19	20.76	1,328,630.20	1,328,630.20
			04				Pressure Regulator Sub-Subsystem	41.03	8.96	15.40	65.38	0.58	4.79	5.24	2.14	12.76	0.32	78.47	2,102,998.40	2,102,998.40
4		04					Low Pressure Circuit Subsystem	140.91	24.01	72.11	237.03	1.28	13.76	14.80	8.53	38.36	2.38	277.78	1,489,698.00	1,489,698.00
			01				Distribution, Low Pressure Sub-Subsystem	82.05	4.36	5.28	91.69	0.51	5.81	6.00	2.52	14.84	1.97	108.50	577,268.40	577,268.40
			02				Fuel Rails Sub-Subsystem	46.46	7.07	8.74	62.26	0.38	4.10	4.41	2.71	11.60	0.39	74.26	901,429.60	901,429.60
			03				Fuel Injectors Sub-Subsystem	12.40	12.59	58.10	83.08	0.38	3.84	4.39	3.30	11.92	0.02	95.02	11,000.00	11,000.00
5		05					Controls Subsystem	221.24	23.89	22.57	267.70	1.32	12.94	14.07	6.70	35.03	0.53	303.26	1,687,144.10	1,687,144.10
			01				Control Module Sub-Subsystem	192.11	2.37	8.85	203.33	1.11	10.18	11.51	5.63	28.44	0.19	231.96	1,047,144.10	1,047,144.10
			02				Wire Harnesses Sub-Subsystem	29.14	21.51	13.72	64.36	0.21	2.77	2.55	1.06	6.60	0.34	71.30	640,000.00	640,000.00
							TOTAL	1,513.20	139.38	306.28	1,958.86	40.20	109.15	107.32	45.65	302.32	15.03	2,276.20	17,817,628.83	17,817,628.83