Conversion and performance evaluation of a hydrogen powered Ford F-250 pickup truck

Julian J. L. Gardner

University of Nevada, Las Vegas

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CONVERSION AND PERFORMANCE EVALUATION
OF A HYDROGEN POWERED
FORD F-250 PICKUP TRUCK

by

Julian J. L. Gardner

Bachelor of Science, Mechanical Engineering
University of Nevada at Las Vegas
2005

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Mechanical Engineering
Department of Mechanical Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada Las Vegas
December 2007
UMI Number: 1452244

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Julian J.L. Gardner

Entitled

Conversion and Performance Evaluation of a Hydrogen Powered Ford F-250 Pickup Truck

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

Examination Committee Chair

Dean of the Graduate College

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ABSTRACT

Conversion and Performance Evaluation of a Hydrogen Powered Pickup Truck

By

Julian Gardner

Dr. Robert Boehm, Examination Committee Chair
Distinguished Professor, Mechanical Engineering
University of Nevada Las Vegas

The following thesis details all design, fabrication and analysis necessary for the conversion of a Compressed Natural Gas (CNG) powered full size pickup truck to run on compressed hydrogen gas. As an industry for hydrogen powered vehicles develops, adherence to a specified set of safety regulations is necessary to ensure the safety of vehicle end users. Currently accepted standards for hydrogen vehicle safety follow regulations put forth by NFPA for CNG powered vehicles. The design of the fuel system follows applicable hydrogen and CNG regulations. A potentially revolutionary fuel delivery system that consolidates a gaseous fuel injector and a spark plug is to be employed on this vehicle.

A device of this type has the potential to greatly simplify future hydrogen vehicle conversions. Electronic sensors implemented in the system provide a means for leak detection around the location of the tanks. A fuel cell and a bank of three super capacitors have been installed to replace the alternator and battery. Replacing the alternator with a fuel cell converts the chemical energy of the hydrogen fuel already
stored on the vehicle to electrical energy more efficiently than using the engine to convert chemical energy into mechanical energy then into electrical energy. The fuel cell was a 1.2 kW PEM stack type produced by Ballard. Computer control of the engine is accomplished via the factory computer already installed in the truck. Programming a fuel table custom to hydrogen is accomplished via an aftermarket reprogramming module and complementing software. The initial fuel table is determined from thermodynamic relations pertaining to compressible flow. Preliminary ignition timing tables were obtained from approximations of hydrogen flame speed scaled to the density of the air fuel mixture. Included in this thesis are all design criteria, analysis and recommended methods for modeling engine performance.
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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Variable/ Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{ref}}$</td>
<td>Reference intake valve cross-sectional area</td>
</tr>
<tr>
<td>AFR</td>
<td>Air to Fuel Ratio</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineer</td>
</tr>
<tr>
<td>ATDC</td>
<td>After Top Dead Center</td>
</tr>
<tr>
<td>BTDC</td>
<td>Before Top Dead Center</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>CA</td>
<td>Crank Angle</td>
</tr>
<tr>
<td>CER</td>
<td>Center for Energy Research</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>$d$</td>
<td>Bolt or Nut Significant Diameter</td>
</tr>
<tr>
<td>$D_e$</td>
<td>Tube Outer Diameter</td>
</tr>
<tr>
<td>$D_V$</td>
<td>Intake valve diameter</td>
</tr>
<tr>
<td>ECM</td>
<td>Engine Control Module</td>
</tr>
<tr>
<td>$f$</td>
<td>Maximum Allowable Wall Stress</td>
</tr>
<tr>
<td>GHG</td>
<td>Green House Gas</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>$L_V$</td>
<td>Intake valve lift</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LFL</td>
<td>Lower Flammability Limit</td>
</tr>
<tr>
<td>LVVWD</td>
<td>Las Vegas Valley Water District</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
</tr>
<tr>
<td>$M_{\text{H}_2}$</td>
<td>Molecular Mass of Hydrogen</td>
</tr>
<tr>
<td>$m_{\text{th}}$</td>
<td>Mass, air in vicinity of throttle plate</td>
</tr>
<tr>
<td>$m_{\text{ap}}$</td>
<td>Mass, air in vicinity of intake valve</td>
</tr>
<tr>
<td>$m_r$</td>
<td>Reference mass of air, found in expression for air mass flow rate</td>
</tr>
<tr>
<td>$m_a$</td>
<td>Mass, air</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass, air in intake manifold; Mach number</td>
</tr>
<tr>
<td>NFPA</td>
<td>National Fire Protection Agency</td>
</tr>
<tr>
<td>NGVA</td>
<td>Natural Gas Vehicle Association</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>PEM</td>
<td>Polymer Electrolyte Membrane</td>
</tr>
<tr>
<td>PRD</td>
<td>Pressure Relief Device</td>
</tr>
<tr>
<td>PRV</td>
<td>Pressure Relief Valve</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>$\tilde{R}$</td>
<td>Universal Gas Constant</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions Per Minute</td>
</tr>
<tr>
<td>t</td>
<td>Time or thickness, specified in each case</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>TDC</td>
<td>Top Dead Center</td>
</tr>
<tr>
<td>UNLV</td>
<td>University of Nevada at Las Vegas</td>
</tr>
<tr>
<td>s</td>
<td>Tube Wall Thickness</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SCI</td>
<td>Structural Composites Industries</td>
</tr>
<tr>
<td>VE</td>
<td>Volumetric Efficiency</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
</tr>
<tr>
<td>$v_0$</td>
<td>Air flow velocity</td>
</tr>
<tr>
<td>VDC</td>
<td>Volts, Direct Current</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compound</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Air to Fuel Ratio</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of Specific Heats</td>
</tr>
<tr>
<td>$\eta_v$</td>
<td>Volumetric Efficiency</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Air-Equivalence ($= 1/\varphi$)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Shear Stress</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Equivalence Ratio ($= 1/\lambda$)</td>
</tr>
</tbody>
</table>
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I would like to thank Dr. Robert Boehm for the tremendous opportunity to work on a project that exposed me to cutting edge technology and required me to expand my abilities technically and professionally. I would also like to thank my parents and family, whose unfailing support for me served as a source of strength and encouragement. Thank you also to Cameron MacAdams, and Chris Salisbury. Finally, thank you to Ronald Fifield, whose innovative and pioneering spirit over the last three years made many aspects of this project possible.
CHAPTER 1

INTRODUCTION

The following thesis describes all design, fabrication and analysis necessary for the conversion of the fuel system on a Compressed Natural Gas (CNG) powered full size pickup truck to run on compressed hydrogen gas. As an industry for hydrogen powered vehicles develops, adherence to a specified set of safety regulations is necessary to ensure the safety of vehicle end users. Currently accepted standards for hydrogen vehicle safety have been put forth by the National Fire Protection Agency (NFPA), the Natural Gas Vehicle Association (NGVA or NGV) and the American Society of Mechanical Engineers (ASME). These standards have been adapted from natural gas vehicle standards yet are broad enough to include technical and safety issues pertaining to hydrogen as a fuel. The vehicle that is the topic of this thesis will be used on city road and highways, thus the design of the fuel system had to follow appropriate NFPA standards.

Fuel system vent lines were routed in such a manner as to satisfy requirements put forward by the NFPA. Plumbing components for the fuel system were selected that were made of materials suitable for use with hydrogen, per manufacturer’s recommendations. Fuel was delivered through an innovative method which has undoubtedly been attempted, but results have not been reported. Hydrogen used to fuel an internal combustion engine presents unique technical challenges, as its low ignition
energy and high flame speed lend it to backfire and preignition when port injection or carburetor injection are used as the method of fuel delivery. A direct injection method of fuel delivery provides control over combustion and emissions and greatly decreases the likelihood of preignition. Hypotheses are presented in the literature review regarding the physical processes that produce the decreased likelihood of preignition or the formation of NOx. Suggested models for engine modeling and performance evaluation are given. A 1.2 kW hydrogen-powered PEM fuel cell in parallel with three super capacitors was installed to replace the alternator and battery.

Project Background

In 2003 the UNLV Research Foundation formed a research partnership between the UNLV Center for Energy Research (CER), the Las Vegas Valley Water District (LVVWD), Kell’s Automotive and Marine (KAM) and Distributed Energy Systems, formerly known as Proton Energy Systems, for the purpose of establishing and developing a hydrogen filling station on the premises of the LVVWD. Complementing this filling station were three vehicles, each of which has been converted to run on hydrogen. The third in this series of vehicles, a dedicated CNG Ford F-250, was converted from a port injection scheme to one of direct injection. Each of the vehicles was subject to two third party inspections.

Upon completion of the inspections, the third party inspectors made recommendations regarding additional safety measures to be implemented or specific safety standards to be followed and summarized these recommendations in the form of a formal letter. A formal letter was drafted and eventually submitted in response to the recommendations of the third party. Included in this letter was an itemized response to
each recommendation detailing action taken or describing reasoning behind refusal to follow a given recommendation. Standards to which the F-250 had to adhere were considerably more stringent, as the vehicle was to be driven on local roads and highways. Details on the standards followed as well as details on the original condition of the vehicle will be given in a later section.

As a benchmark for comparison, this converted Ford F-250 will be compared to an F-250 factory modified to run on compressed natural gas (CNG). It was a goal of this project to utilize direct cylinder injection as the method of fuel delivery in this particular vehicle conversion. Specific details on the injection system and fuel system related to conversion and performance will be given in their respective sections. Establishing a framework for this project in the move toward the proliferation of hydrogen as a viable renewable fuel was established through a review of pertinent literature.
CHAPTER 2

LITERATURE REVIEW

The following is a discussion and analysis of publications pertinent to all of the elements of this vehicle conversion project. Common to all literature pertaining to the topics of hydrogen ICE performance and hydrogen powered vehicle performance was the topic of green house gas (GHG) emissions reduction. Schafer, Heywood and Weiss [2006] highlight the fact that current literature on the subject of vehicle life-cycle analyses does not discuss the effect of additional GHG emissions associated with the production of light weight, fuel efficient vehicles. Based on projections derived from current fuel and materials cost, the group predicted GHG emissions associated with the production of hybrid and fuel cell vehicles would exceed current GHG emissions associated with the production and distribution of current gasoline vehicles. Furthermore, the energy requirements for producing lightweight materials associated with fuel saving vehicles was high enough that emissions reducing strategies would be likely to shift to the production of these vehicles.

Gas reformation as predicted in this publication would take place on a small to medium scale at individual filling stations and would only take place during the hydrogen transition stage. Schafer et al noted that the potential for hydrogen production from solar powered electrolysis of water is limited by high initial costs and will continue to be limited for the next few decades. According to projections given in the
publication, cost competitiveness of these vehicles would be heavily dependent upon oil prices at a given time. The authors also concede the point that consumer willingness to pay a high price could also have a heavy influence on alternative fuel vehicle market competitiveness. They acknowledge a current trend in the vehicle market to trade off fuel economy in favor of comfort and performance and with this trade off is a higher retail price. Consumer willingness to pay a higher price adjusted the projected hydrogen ICE market penetration to 5 years and the hydrogen fuel cell vehicle market penetration to 10 years. Both projections were based on the current and projected vehicle technologies [Schafer et al., 2006]. Based on projected ICE advancements in the areas of efficiency and fuel economy, the authors made the conclusion that, barring a dramatic increase in crude oil prices, future ICE powered vehicles will have low enough GHG emissions and a low enough cost that more advanced power plants will not be competitive for at least another 40 years. An analysis authored by Granovskii, Dincer and Rosen [2006] made similar assumptions regarding hydrogen production, but arrived at different conclusions due to a lack of projections on future technological developments.

Granovskii et al found that when comparing conventional, hybrid, electric and fuel cell vehicles on the basis of projected GHG emissions and life cycle and fuel cycle cost, fuel cell vehicles were eliminated on the basis of cost and emissions released during the production phase. Environmental and economic factors were derived and normalized between representatives of the four types of vehicles considered. Results of this study indicated a strong dependence of emissions and cost competitiveness upon the method of electricity production to be used by each vehicle power plant. Due to this
dependence, electricity production was considered in three scenarios: (1) production from renewable sources including nuclear energy; (2) 50% production from renewable sources and 50% from natural gas with an efficiency of 40%; (3) all electricity produced from natural gas with an efficiency of 40%. The authors determined that the conventional gasoline vehicle and the hydrogen fuel cell vehicle were not competitive on the basis of emissions produced during production and use.

Granovskii et al. cited emissions figures from Pehnt [2001] and averaged them over the projected useful life of the fuel cell vehicle. Emissions produced during the production phase cancelled the low emissions produced by the vehicle over a set annual driving distance. Additionally, the prohibitively high initial cost of a fuel cell vehicle overshadowed other costs imparted to the consumer over the life of the vehicle [Granovskii, 2006]. Considering the three aforementioned electricity generation scenarios, the authors found the first two cases to be instances where hybrid and electric vehicles could be competitive. The third scenario represented a case where the hybrid vehicle had significant advantages over the other three vehicles. The group came to the conclusion that an electric car with the capability for on-board electricity generation could be competitive in a situation where all electricity generation was produced from fossil fuels. The on-board generation scheme proposed by the group consisted of a gas turbine connected to a high capacity battery and an electric motor. According to the authors, cycle efficiency would have to fall in the range of 50% to 60% to make it practical. Analyses by Schafer et al. [2006], Granovskii et al. [2006] and Pehnt [2001] did not explicitly reference the difference in the cost of materials used in hydrogen vehicular fuel systems over gasoline fuel systems, but each of the studies made adequate
assumptions to include the additional cost associated with hydrogen vehicular fuel systems. The most commonly used material in hydrogen vehicular fuel systems is stainless steel. Its resistance to embrittlement and high strength make it an attractive choice for fuel line fabrication, but these two characteristics come at a considerable additional cost over materials currently used in gasoline vehicular fuel systems.

Given the unique flammability and mechanical properties of hydrogen, due consideration must given to the design of vehicular fuel systems in hydrogen powered vehicles. In a publication by J. G. Hansel, G. W. Mattern and R. N. Miller [1993] of Air Products and Chemicals, Inc., flammability and embrittlement properties of hydrogen were examined in the context of a vehicular fuel system design. The authors highlighted the fact that the small molecular size of hydrogen enhances its propensity to leak. Given the wide flammability range of hydrogen, this propensity to leak creates a fire safety concern in vehicular fuel systems. Ironically, its small molecular size gives it a high diffusivity and high buoyancy. These two properties coupled together have the effect of diluting any hydrogen leaked to atmosphere thus making ignition at the source of a leak unlikely. Furthermore, the effects of buoyancy and diffusion are important only in the case of a stationary vehicle. In the case of a moving vehicle, light currents resulting from slow vehicle motion or the radiator cooling fan will generally dominate other mechanisms that act to decrease the concentration of hydrogen coming from a leak [1993]. According to the authors, hydrogen leaks fall into one of two categories. Excluding catastrophic failures, leaks typically involve failures of metal on metal seals and failures of nonmetal seals.
Between the two types of leaks, those caused by failures of nonmetal seals can be more significant, as the leaking gas has the potential to displace seal material. The authors contend that leaks exhibit turbulent flow, which in turn causes rapid mixing and rapid dilution. Without a supporting calculation, Hansel et al also claim that there is a direct correlation between the concentration of hydrogen released by the leak and the distance from the leak [1993]. Concentration decreases with distance presumably as a decreasing exponential, but the authors did not give a functional form for the relationship. Fire and safety hazards associated with hydrogen powered vehicles are not limited to leaks in the fuel system but also include on-board storage systems.

The authors assess the different concerns associated with various types of storage system, but only the compressed storage will be discussed here, as it was the method used in the vehicle that is the topic of this thesis. Due consideration must be given to materials of construction for storage vessels, as hydrogen embrittlement limits the scope of materials suitable for use with hydrogen. Additionally, the pressure vessels must meet US DOT or other equivalent standards [1993]. Tanks used on this truck satisfy standards set forth by the US DOT regarding the transport of hydrogen. Specific details on the standard will be given in a later section. Compatibility with hydrogen gas must not only be design criteria for the materials of construction of the tanks, but also for the fuel and vent lines. Fuel lines must be ductile in order to withstand impact forces without breaking, and should be properly supported to minimize vibration associated with a standard driving cycle. Joints in the fuel lines should also be able to withstand the same vibration, and joints in any piping system should be kept to a minimum. The authors contend that threaded connections and flanges are undesirable and should be
avoided. Instead, crushable seals and flared fittings are considered far better, but for hydrogen piping systems brazing is the best option. Furthermore, certification and leak testing procedures should be followed in assembling the piping systems. All tubing in a given system should be able to withstand the tank working pressure, as regulator failure can expose components downstream of the regulator to pressures higher than that for which they were designed.

Hansel et al [1993] highlight the importance of incorporating instrumentation in the fuel system that can handle pressure regulator failures. Such instrumentation would include pressure relief valves and tubing upstream of the regulators “designed to withstand failure of the preceding regulator.” Vent lines attached to pressure relief devices must also be designed to tolerate higher pressures reached in the event of regulator failure [NFPA, 2006]. Tank pressure reached during vehicle fire is significantly higher than working tank pressure, therefore emergency vent lines must also be able to tolerate pressures approximately one and one-half times the working tank pressure and should be separate from vent lines used for regulator failure. Vent lines should be located in such a way as to direct vented hydrogen away from people and air intakes [Hansel, 1993]. These locations are typically in a central location on any given vehicle, as this placement negates the hazard of a person standing in front of a vent line. Vent lines should be directed upward as to utilize the buoyancy of hydrogen in air. Common scenarios involving venting are typically initiated by fire or by vehicle collision.

The authors emphasize the importance of fuel tank location as being critical to the integrity of the storage system should the vehicle ever be involved in an accident. In
general, tank locations should be away from the vehicle perimeter. Further, standards originally set forth by the NFPA require the tank mounting system to be able to withstand a load of 8g in any direction [NFPA, 2006]. Design details on the mounting system employed on the F-250 will be discussed in a later section.

Publications regarding experiments and developments in hydrogen internal combustion engines are numerous, but characteristics of the results presented in each publication are common to all of them. A publication by Verhelst and Sierens [2001] concerning the optimization of a hydrogen engine made the claim that when port injection is the fuel delivery method used, backfire can only be completely avoided if operating with a lean air-fuel mixture. The authors employed an engine control module (ECM) to exercise full control over the engine. Such a control scheme would be ideal for an optimization study. Computer control of fuel and ignition timing allowed the authors to control ignition timing based on manifold pressure and engine speed. Experimentally determined ignition timing demonstrated a stronger dependence of ignition timing on manifold pressure than on engine speed, but this could in part be due to a wide range of lean air-equivalence ratios employed in the control system fuel tables. The control scheme used in the ECM included feedback variables that allowed for dynamic adjustment of operating parameters in response to changes in environmental conditions [2001]. White, Steeper and Lutz [2006] published a technical review detailing recent achievements in hydrogen internal combustion engines.

Based on results taken from other publications, the authors predict minimum ignition energies of less than 0.02 mJ for typical engine pressures and temperatures. Additionally, ignition energy varies inversely the square of pressure and inversely with
temperature. In agreement with the conclusions of the publication by Verhelst et al. [2001], the authors highlight the difficulty of operating a hydrogen PI-ICE at or near the stoichiometric air fuel balance in the absence of preignition events. It is generally accepted that direct injection, while decreasing thermal efficiency, decreases the likelihood of preignition events and improves control over vehicle emissions.

Al-Garni [1994] developed an in-cylinder hydrogen injection system based on mechanical actuation of a rotational valve. The rotational valve utilized a sealing mechanism whereby a circular shaft with a flat cut in it was in exact press fit contact with an ABS plastic housing. The ABS housing featured an inlet port that was collinear with the shaft and an outlet port oriented perpendicular to the shaft. Hydrogen was allowed to flow through the outlet port when the orientation of the flat on the shaft was in the vicinity of the outlet. A check valve protected the mechanical valve from high combustion temperatures and pressures. The sealing mechanism in the check valve consisted of a free-floating disc outfitted with four holes through which incident hydrogen would flow. Spacing of the holes was selected to allow hydrogen to flow when the pressure difference was in the direction of the cylinder (i.e. injection during the compression stroke) and seal off hydrogen flow when the pressure difference was in the direction of the solenoid valve (i.e. pressure rise immediately following ignition).

Temperature measurements taken on a tube connecting the injector to the controller with and without the disc demonstrated the positive effect of installing the disc. The temperature of the tube where it mated with the injector was the same with and without the tube. The temperature similarity could be attributed to heat conduction through the injector and the tube. At a distance of 3.94 in (100 mm) away from the injector, the
temperature of the tube with the disc installed was 104°F (40°C) cooler compared to the case where the disc was not installed. Pressure traces taken of in-cylinder pressure were as high as 11600 psi (80 MPa). Testing was carried out on a Briggs and Stratton 319 cc single cylinder engine that had a bore of 3 inch (76.2 mm), a stroke of 2.75 inch (69.8 mm) and a compression ratio of 6.9. Green and Glasson [1992] designed and tested a custom designed and fabricated injector that served as inspiration for the work completed by Al-Garni [1994].

Green et al. [1992] detail two different methods for controlling the operating air-fuel ratio, including variation of the injection pressure and variation of the injection duration. Varying the injection pressure could be achieved by throttling before the injector or varying the injector lift. Both of these options involve a process that requires precise movement of a valve. This precise motion would require an equally precise feedback control system to ensure that proper positioning of the valve was achieved. In the best interests of simplifying the final design, such an option should be disregarded. Varying the injection duration could be achieved by means of a fast acting solenoid valve activated by a square wave pulse of a controlled width. Fast as considered here would have a turn-on time between 2 and 16 ms. Equipment requirements for this option are much more simple than the first option, which makes it a more attractive option. Green et al. [1992] designed an injection system that utilized variable injection duration. A flow area that would cause a sonic flow regime was used, as this would maximize the mass flow rate through the injector.

An injection pressure of 1160 psig was selected, as this would ensure sonic flow through the injector nozzle at any time during the compression stroke. The sealing
mechanism within the injector consisted of a spherical poppet pressing against an o-ring seat where the cross-section of the o-ring was a four-legged star shape. A custom solenoid valve was designed and implemented to complete the assembly. It was experimentally determined that the solenoid coil operated more efficiently if its tendency for self-heating could be diminished by external cooling. In response to this observation, the coil was outfitted with a dedicated cooling water passage. Experimental results given by the authors revealed in-cylinder pressures as high as 870 psi (60 bar) for WOT at 2000 RPM. Tests on the injector carried out on a Ricardo E6 engine.

Mohammadi, Shioji, Nakai and Tabo [2007] published the results of a similar study, however the effects of varying injection and ignition timing on in-cylinder pressure, emissions and thermal efficiency were also under consideration.

Mohammadi et al [2007] used an electromagnetically-actuated injector produced by Westport Innovation, Inc. installed on a 52 cubic inch (857 cc) displacement engine. The device was configured for direct injection, as this would negate the effects of power loss and unplanned ignition events such as preignition and backfire typically associated with a port injection type configuration. For a given equivalence ratio and an injection timing of 300 CA degrees BTDC, retarding ignition timing had the effect of increasing NOx, maximum in-cylinder pressure, brake mean effective pressure, pressure rise rate and thermal efficiency. The production of NOx could be attributed combustion temperatures reaching high enough levels to induce thermal dissociation of nitrogen in the air charge. These higher combustion temperatures were a direct result of retarding the ignition timing. Advancing injection timing to 130 CA degrees BTDC had the effect of decreasing NOx production at higher equivalence ratios, slightly increasing maximum
in-cylinder pressure and increasing brake mean effective pressure. Furthermore, volumetric efficiency remained at approximately 90% over a range of equivalence ratios from 0.3 to 0.7 [Mohammadi et al., 2007].

A trend in results similar to that presented by Mohammadi [2007] was published by Yi, Lee and Kim [1996]. In addition to volumetric efficiency improvements over port injection, Yi et al present the conjecture that hydrogen gas injected at a sufficiently high pressure will rapidly cool as it expands in the cylinder. This phenomenon had the effect of cooling the air- hydrogen mixture immediately prior to combustion and hindering NOx formation. In hydrogen internal combustion engines tuned for low emissions, this cooling effect serves as a major advantage of direct cylinder injection over port injection. Literature on vehicle conversions to hydrogen power was relatively scarce compared with issues pertaining directly to engine tuning, direct injection and emissions of hydrogen internal combustion engines. In a publication by Billings, Hatch and DiVacky [1983], a gasoline powered postal vehicle was converted to run on an electronically controlled carburetor injection system.

A parameter of particular interest to Billings et al. [1983] was hydrogen fuel mileage as compared to gasoline on an equal energy basis. The results of 22 runs over a two month period revealed an average efficiency improvement over the vehicle’s gasoline performance of 21%. As previously stated, a frequent problem with port or manifold injection approaches is back fire and preignition. In order to hinder these phenomena, a water induction system was installed that used the original gasoline carburetor capillary tubes. The water induction system acted to cool the air- fuel mixture immediately preceding ignition thus decreasing the likelihood of preignition. While this system was
reported to eliminate uncontrolled ignition events, it is likely that it decreased
volumetric efficiency and power output by displacing air that could have otherwise gone
toward producing useful work. Also among the issues considered by Billings et al.
[1983] was oil contamination by product water. Given the fact that the product of
hydrogen combustion was water and additional water was being added to the incoming
air stream through the water induction system, the abundance of water was considered
as a potential source for engine damage. Typical schemes for reducing the concentration
of water that leaks past the piston rings and makes it to the crank case consists of
heating the oil to a temperature near the boiling temperature of water. Field testing of
the vehicle revealed that a standard PCV system was sufficient to remove water from
the crank case.

Work on modern hydrogen internal combustion engines and the various methods for
fuel delivery are extensive and have continued to the present time for decades.
Functional and safety requirements for hydrogen powered vehicles have been under
increasing scrutiny in the past decade, as the unique properties of hydrogen require
standards that match the unique new technical issues it poses.
CHAPTER 3

ORIGINAL VEHICLE CONFIGURATION

Figure 1. Outside condition of vehicle in as-received condition.

Figure 2. Truck bed in as-received condition.
CNG powered Ford F series trucks within the LVVWD fleet have been factory converted from gasoline power to run on CNG. The truck in question was a dedicated CNG powered vehicle. CNG fuel tanks on the truck consisted of a ½” thick steel shell surrounded by hoop layers of fiberglass. There was a total of three tanks, two in the bed and one on the under side of the bed. Based on tank outer dimensions and wall thickness, total tank inner volume was estimated to be 10,460 cubic inches. Working pressure for the tanks was 3600 psig. Tanks in the bed were supported by a belly mount rack of unknown manufacturer, while the tank under the bed was of the same diameter as the two in the bed, but it was shorter in length and supported by a bracket of similar form. Each tank was equipped with its own solenoid valve and manual isolation valve. The tanks were plumbed into stainless steel hard line of the fuel system through flexible hose brazed to the hard line. This hard line was 3/8” in diameter and of a relatively thin wall, estimated to be 0.049”. At points where the fuel lines passed through the bed, the flexible hose was protected from chafing and vibration with a rubber grommet. Flexible hose also made the transition between the hard line and the pressure regulator. Incoming gas was filtered then fed into the regulator. Pressure regulation for the fuel system took place upstream of the tanks, under the bed.

The factory pressure regulation system decreased the fuel pressure from the tank pressure to the port injection pressure of 95 psi. In cold weather conditions, certain chemical components of compressed natural gas condense and foul fuel injectors. This

<table>
<thead>
<tr>
<th>Table 1. Vehicle specifications</th>
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<tbody>
<tr>
<td>YEAR, MAKE, MODEL:</td>
</tr>
<tr>
<td>ENGINE:</td>
</tr>
<tr>
<td>FUEL:</td>
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<tr>
<td>FUEL CHARGING:</td>
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phenomenon was hindered by the addition of engine coolant lines that were plumbed directly through the regulator. The temperature difference between the fuel and the coolant transferred heat into the fuel sufficient to raise the temperature of the fuel and evaporate any liquefied fuel components. Downstream of the regulators, additional flexible lines vibration isolated the fuel rails. A primary flexible line mated with a distribution block that teed off into each side of the engine. Flexible lines coming out of this block were brazed to the fuel rails. Four injectors of an unknown manufacturer were mounted into each fuel rail, which were mounted into the intake manifold for a port injection scheme. One of the CNG injectors is illustrated in Figure 3. The engine control module (ECM) actuated the injectors based on timing dictated by a program uploaded to the computer at the factory.

Figure 3. CNG injector produced by Ford. Unknown number of hours of operation.

The ECM determined fuel injector pulse widths based from values programmed into a set of two tables. The first table expressed injection duration in terms of crank angle
(CA) as a function of volumetric efficiency (VE) and engine RPM, while the second table expressed equivalence ratio as a function of VE and engine RPM. For a given VE and RPM, the corresponding values from each table were multiplied together to obtain angular duration of injection. Injector turn-on time was fixed. Corrections to fuel flow into the cylinder could be made according to manifold air pressure and temperature. Flame speed of a given fuel follows an approximately inverse relationship to density of the air-fuel mixture, which indicates ignition timing at a lower load and lower engine speed would have less advance than timing at a high load and higher engine speed.

![CNG MBT Spark Timing](image)

**Figure 4.** This figure illustrates CNG ignition timing optimized to maximize brake torque.

Ignition timing is typically determined by stoichiometric flame speed. The ignition timing for CNG used in the Ford F-250 can be found in Figure 4. The trend in Figure 4 is consistent with the aforementioned relationship between density of the air-fuel mixture and the flame speed. As load (VE) and RPM increase, ignition timing...
approaches TDC. Spark retard reaches a maximum at maximum RPM and minimum load. The roughness of the surface in Figure 4 is can be attributed to a turbulent flow regime in the incoming air stream causing turbulence in the cylinder after the intake valve closed. Assuming a stoichiometric air- fuel mixture, ignition timing and injector timing are linked in a port injection scheme through VE and RPM, however the presence of a computer- controlled automatic transmission also affects injection duration and spark timing over the range of engine loads and RPM.

![Diagram](image)

**Figure 5.** This figure illustrates injector closing as a function of VE and RPM.

Figure 5 illustrates what the author hypothesizes is to be an effect of an automatic transmission attached to the engine. Injector duration remains constant over the range of RPM from 2000 to 2500. At a certain engine RPM and VE, the transmission is programmed to shift into a higher gear, thus decreasing engine RPM and increasing VE. Figure 6 illustrates a programmed richening of the air- fuel mixture at a higher RPM. Tables downloaded from the ECM indicated that the engine does not typically reach speeds sufficiently high as to reach this region of richening.
Figure 6. This figure illustrates lambda as a function of VE and RPM.

A functional form of the equation used in control schemes in the Ford ECM was not given in literature supplied by SCT. Considering all pertinent variables contained in the Ford ECM program, an equation given by Nicolao et al. [1996] was sufficient for black-box identification purposes. This equation is given in a later section on Ford ECM programming for hydrogen. As a later section will illustrate, the general shape of the surface plots given in Figure 4 through Figure 6 was preserved, as the shape of each of these plots has implications regarding the relative influence of measured variables on feedback-controlled outputs.
HYDROGEN FUEL SYSTEM DESIGN

Design Considerations

Wetted materials in the fuel system obviously had to be compatible with hydrogen. Stainless steel made an ideal choice, as its resistance to embrittlement combined with high strength and low bulk made it an attractive option. Joints in the system had to be field-serviceable and not require specialized certifications to install or service. Emphasis was placed on creating a system the mechanics at the water district could service when necessary. In terms of vibration resistance and long term joint integrity, brazed joints in piping systems are known to be superior to fitting joints, but they require installation by a certified welder and hydro-testing once a certain number of operating hours has been exceeded. Tubing employed in the system had to have a working pressure of at least 5000 psig (350 bar), and all tube fittings had to withstand the same working pressure as the tubing. A common trend in industry among tube fitting manufacturers is rating different components of a given fitting to different pressures. An example of this trend can be found in the case of an adapter fitting that adapts a male pipe thread to a compression tube fitting.

In such a case, the pipe threads can be rated to a lower maximum pressure than the compression end of the fitting. This issue was encountered and is addressed in a later section. Manufacturers’ specifications were used in selecting tubing and fittings, but
factors of safety were verified using equations derived from theorems of mechanics of materials. Tubing rated to a sufficient working pressure had a large enough wall thickness relative to its outer diameter that variation of the hoop and radial stress had to be taken into account in calculating an effective factor of safety. The calculations for an effective factor of safety can be found in the following section. Factors of safety and functional requirements for specific components had to follow standards set forth by NFPA and DOT.

Pressure gauges employed in the system had to be able to read at least 1.2 times the system design pressure, as detailed in NFPA 52, item 5.6.1. Actuation devices within the gauges were bourdon tubes, as a bourdon tube is the most common gauge actuation method in industry. NFPA regulations prohibit the use of pipe threads in hydrogen service above 3000 psig (345 bar), except where instrumentation is not available with straight threads.

**Implemented Design**

The piping and instrumentation diagram for the implemented fuel system design can be found in the appendix. Tubing was selected to meet or exceed a working pressure of 5000 psig (approximately 350 bar). All tubing and fitting materials were 304 and 316 grades of stainless steel and selected for their suitability for use with hydrogen gas. Selection criteria for the grades were based on manufacturers' recommendations as given in the Appendix. 3/8” tubing was selected as the primary fuel line size for its higher working pressure for a given wall thickness while simultaneously not being so small as to induce relatively high flow velocities within the tube.
Primary fuel lines were plumbed in such a way as to minimize their length and in doing so minimize the volume of hydrogen they contained. U-bends were employed between consecutive tanks to allow for thermal expansion and contraction during filling and operation. Installation of the tubing followed guidelines put forth in the appendix of the tube fitting catalog published by the Parker-Hannifin Company.

Figure 7. Tanks installed in truck bed. Five tanks were needed to keep the range of the vehicle up to some acceptable level.

Figure 8. Tanks and fuel system installed in truck bed. The fuel system was not yet complete in this picture, and the APU fuel cell was not installed.
NGV standard (insert standard number) required that compressed gas fuel tanks be supported by a structure that can withstand accelerations of 8g’s. In accordance with this standard, a base fuel tank support structure was constructed from steel strut channel and steel box beam, as illustrated in Figure 9. This base structure was complemented by 3/16” thick steel straps fastened to the tanks in a belly mount configuration, as illustrated in Figure 7 and Figure 8. As a mounting system, the steel belly mount straps seen in the figures were provided by the tank manufacturer and were certified to NFPA 52, “Compressed Natural Gas Vehicular Fuel Systems.” Regarding the previously mentioned standard of withstanding an 8g load, it was assumed that the tank and bracket manufacturers had followed all applicable gaseous fuel transport standards. Adjacent tanks were fastened together using SAE 1/2”-13 Grade 8 nuts and bolts. Considering the primary mode of failure to be shear failure of the bolt and nut threads, shear stress on these threads were determined from the equation for thread shear stress:

\[ \tau = p \cdot \pi \cdot d \cdot (0.75 \cdot t) \]  

(1)

Given the above calculated stress and using the yield strength of Grade 8 bolts, the factor of safety for this nut and bolt combination is 11. Nylon lined nuts were selected for their vibration resistance. Mounting point locations on the base structure were determined after the rack was constructed. Individual mounting feet were constructed and welded to the base structure. ABS plastic pads placed between the feet and bed provided protection to the sheet metal of the bed and hindered tearing or deforming of the bed around the mounting holes. Two mounting holes previously used by the CNG
bed mounting bracket were used in mounting the base hydrogen tank support. To hinder bed sheet metal deformation and loss of integrity, these two bolt holes had tubes welded to them, through which the mounting bolts would pass. This strategy was used to mount the hydrogen tanks. Short sections of steel pipe were cut and used to prevent the bolt from crushing the sheet metal when it was tightened. Each section of pipe was cut to span a gap between sheet metal of the bed and the vehicle frame.

![Figure 9](image_url)

Figure 9. This figure illustrates base tank support structure as modeled in Solid Works. It is shown here without mounting feet.

The tanks were plumbed in series to minimize the number of fittings used in the system, as illustrated in Figure 8. Each of the tanks was produced by Structural Composites Industries (SCI) of Pomona, California. Hydrogen tanks produced by this company were DOT E-10945-5000 certified for the transport of hydrogen. Each tank consisted of an inner aluminum liner with a ninety liter nominal water volume. Surrounding the inner liner was a layer of carbon fiber in an epoxy resin matrix, which in turn was wrapped longitudinally and circumferentially in a layer of Kevlar to give
each of the tanks surface toughness and limited UV protection. This outer layer of fiberglass can be observed in Figure 7 and Figure 8. The tanks were rated to a working pressure of 5000 psig (insert published value) and rated to a maximum pressure of 8333 psig. Each featured two ports consisting of an aluminum boss welded to the aluminum liner, which was outfitted with an inner chamfer for an O-ring seal. The first of these two bosses was plugged while the other was outfitted with a manual valve. Manual valves installed in these tanks were the (insert model number) model produced by GFI. Each valve was approved by NGV and TUV and was originally produced and certified for use with CNG. In order to keep pace with the expanding alternative fuel market, GFI recertified all of their valves they had in production for use with gaseous hydrogen. As a result of this recertification process, valves installed in the tanks purchased from SCI are each rated to a maximum pressure of 14,400 psig. Valve specifications can be found in the appendix.

Valve actuation was performed through plastic handle oriented with its axis collinear with the tank. Additionally, each valve had installed in it a heat-activated pressure relief device (PRD), the orientation and location of which is illustrated in Figure 10. The presence of this device is in fulfillment of current NGV and NFPA standards, which require that safety provisions be implemented that allow for the safe venting of hydrogen in the event of fire. In accordance with this requirement, each tank valve was equipped with a PRD.
In its most common form, a PRD contains a metal membrane that melts away in the event of fire or tank overpressure. Thermal activation of this device occurs at a gas temperature of 217 °F (103 °C). Given the valid assumption of constant volume and assuming the temperature of the gas to be the temperature to which the PRD is rated, the ideal gas relationship solved for temperature was used to demonstrate that hydrogen in the tank would reach this temperature in the event that the tank was pressurized to a level approaching its maximum rating:

$$ T = \frac{P \cdot V \cdot M_{H_2}}{m \cdot R} $$

(2)

Temperature as predicted by this relationship was approximately 400 °F, which would thus cause the PRD to open and vent its contents. All pressure relief devices installed in the tank valves were produced by GFI and were ported for an SAE 45 degree male flare for ½” tube. Vent tube to be coupled to the PRD was equipped with a 45 degree flared
tube nut and flared using a heavy duty flaring tool. Proper sealing between the tube and
the PRD was ensured via the use of a 45 degree copper crush washer. Tubing coupled
with these pressure relief devices was selected to have a working pressure well above an
expected venting pressure.

Assuming a gas temperature of the published value at which the PRD will open, the
pressure at the inlet of the PRD can be calculated to a reasonable approximation from
the ideal gas relationship as follows:

\[ P_2 = P \cdot \frac{(T_2 + 273)}{(T_{\text{std}} + 273)} \]  

(3)

where \( T_2 = 103 \, ^\circ\text{C} \), \( T_{\text{std}} = 20 \, ^\circ\text{C} \), \( p = 350 \) bar and \( p_2 \) is the pressure in the tank at a
temperature of \( T_2 \). The above relationship yields the pressure in the tank to be \( p_2 = 449.1 \) bar. Assuming an isentropic pressure drop and a sonic flow regime through the
PRD, the following relationship can be used to calculate the pressure at the outlet of the
PRD:

\[ p_3 = p_2 \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \]  

(4)

where \( p_2 \) has been calculated above and \( \gamma \) is the ratio of specific heats. Given a ratio of
specific heats for hydrogen of 1.4, the above equation yielded the outlet pressure of the
PRD to be \( p_3 = 237 \) bar. This pressure was used to determine a factor of safety for the
emergency vent lines. This calculation did not take into account additional pressure
losses due to friction in the PRD or an additional pressure drop though the vent line due to friction and gas expansion. Both of these sources of error acted to increase the factor of safety of the vent line by further decreasing the outlet pressure of the PRD and by further decreasing the pressure to which the vent line is exposed. Considering a given wall thickness, outer diameter and pressure, hoop stress in a thick walled pressure vessel will always be the greatest of the three principle stresses. According to Annaratone, a minimum tube wall thickness, $s$, could be calculated using the following equation:

$$s = \frac{D_e}{2} \cdot (1 - e^{-\frac{p}{f}})$$  \hspace{1cm} (5)

where $D_e$ is the tube outer diameter, $p$ is the internal pressure to which the tube is exposed and $f$ is the allowable stress as determined from the yield stress and a factor of safety. Using a factor of safety of 3 and the vent line pressure calculated above, the above equation yielded a wall thickness of 0.064in. This was the basis for vent line selection. One additional vent line was installed to serve the purpose of a low pressure service vent and an emergency vent in the event of injection pressure regulator failure. This vent line was connected to a manual valve and a pressure relief valve.

A pressure relief valve (PRVs) protected fuel plumbing components from tank pressure in the event of regulator failure. These types of valves differentiate themselves from PRDs by the fact that they are actuated by a pressure difference across an internal piston. The first of the two valves was field adjustable while the second is internal to the fuel cell. Both of these valves opened when pressure inside the valves produced a force that was equal to or greater than the compressive force that each valve spring exerted on
each piston. The field adjustable valve had been set to relieve pressure sufficiently higher than the regulator outlet pressure as to not cause an accidental release, yet simultaneously not high enough to damage components downstream of the regulator. The only PRV in the fuel system was produced by the Parker Hannifin Company and featured a cracking pressure adjustable from 1500 psig to 2250 psig. The second of the two PRVs is internal to the fuel cell and was of unknown producer. It primarily serves the purpose of protecting the fuel cell membrane in the event of regulator failure. It had been installed in such a way as to vent it line pressure over a hydrogen sensor, which in turn shut down the fuel cell.
First stage pressure regulation used a diaphragm type regulator produced Tescom, a division of Emerson Process Controls. It was designed for high flow, tamper proof applications. Its outlet pressure was adjustable from 250 psig to 1500 psig. The tamper proof feature on this device was accomplished through two nuts in place of a knob or handle at the uppermost portion of the regulator body. Outlet pressure adjustment was performed with the lower nut, and once it was set the lower nut was held in place by tightening the upper nut against it. Downstream of the first stage regulator, a second stage regulator further decreased the line pressure to a level suitable for the inlet.
pressure of the internal fuel cell regulator. Second stage pressure regulation decreased
the pressure from the injection pressure to 160 psig. Outlet pressure on this regulator
was fixed, as the fuel cell pressure regulator accepted inlet pressures over a wide enough
range that adjustment of the inlet pressure was not necessary. In the event that the fuel
cell should have to be serviced or removed from the vehicle, this regulator could be
isolated from the rest of the fuel system through a manual valve located at the outlet of
the second stage regulator.

![Injection pressure regulator](image1)

![Fuel cell regulator](image2)

**Figure 12.** Pressure regulators installed in the truck bed.

![Alternative fuel service ball valve](image3)

**Figure 13.** Alternative fuel service ball valve produced by Parker. Each of these valves
were rated to a maximum service pressure of 6000 psig.

Each vital fuel system component was equipped with a manual isolation valve. In
each case, this valve served the purpose of allowing the component it isolated to be
serviced without necessarily having to depressurize the fuel system. Each of these
valves contained polytetrafluoroethylene (PTFE) seals and Buna-N O-rings, as Parker deemed each of these materials suitable for use with hydrogen. All isolation valves were two way style ball valves actuated through plastic handles that had to be turned 90 degrees to open or close the valve. Locations of these isolation valves within the system were as follows:

1. In the truck bed downstream of the fill nozzle. Isolated fill nozzle from system in the event of fill nozzle failure.

2. In the truck bed downstream of the injection pressure regulator. Isolated tanks from injection system and shutoff solenoid valve.

3. In the engine compartment upstream of the injection system. Isolated injection system from fuel system for servicing.

4. In the truck bed downstream of the fuel cell pressure regulator. Isolated the fuel cell for servicing.

Two additional valves in the fuel system were configured to provide an alternate filling point for the vehicle and a low pressure service vent for system purging. The low pressure purge valve was plumbed in parallel with the PRV mentioned in a previous section. This valve served the purpose of depressurizing the system at a pressure sufficiently lower than the tank pressure when service work needs to be performed on the system. The valve at the alternate fill point could also serve as a high pressure purge should it be necessary. End connections on each manual valve were selected to be A-Lok style crimp tube fittings produced by Parker. This style of crimp fitting is related mechanically to a Swagelok fitting, as illustrated in Figure 14 and Figure 15.
The Parker Suparcase back ferrule provides a strong mechanical and anti-vibration hold on the tube. Parker's high-quality silver-plated nut ensures no galling of body threads. Figure 14. Cutaway view of the A-Lok tube fitting produced by Parker. The double ferrule sealing mechanism allows for easier installation and reliability. (Image taken from A-Lok Tube Fittings catalog published by Parker on the company website.)

During assembly of the advanced-geometry design (above), the front ferrule is driven into the fitting body and the tubing to create primary seats, while the back ferrule flanges extend to create a snug grip on the tubing. The back ferrule geometry allows for an improved engineering hinge-pointing action that translates axial motion into radial swaging action on the tube, yet operates with a low assembly torque requirement. Figure 15. Cutaway view of tube fitting produced by Swagelok. This double ferrule design produced by Swagelok is similar to the fitting produced by Parker, as illustrated in Figure 14.

Pressure ratings of the crimp end of these fittings were specified by the manufacturer to be the burst pressure of the tube to which they are attached. As illustrated in Figures Figure 14 and Figure 15, both Swagelok and Parker A-Lok fittings that were used in this system used a double ferrule sealing mechanism that provides for easier installation and better reliability over its single ferrule counterpart. Fittings that used this crimp mechanism to adapt a tube fitting to a threaded port were used throughout the fuel system. Adapters mated to ports on each of the pressure regulators.
were pipe threaded according to the port specifications on the regulators, while adapters mated to the tank manual valve ports were straight threaded according to valve port specifications. Pressure ratings for the threaded end of these fittings can be found in Appendix. Considering the pressure to which the straight threaded fittings on the tank valve ports are exposed to be the working tank pressure, Equation 3 can be used to determine a factor of safety for the threads. Manufacturing standards to which all pipe and straight threads comply can be found in the appendix. Items requiring a straight thread fitting included the tank valves and refueling receptacle.

Figure 16. OPW L series hydrogen fueling receptacle. (Image taken from brochure published on the OPW website)

It was required that the refueling receptacle implemented on this vehicle be compatible with the refueling nozzle already installed at the filling station. An OPW model LW 5000 was installed to satisfy this requirement. This make and model of receptacle features an integral ball bearing style check valve and stainless steel body. It has a maximum allowable working pressure of 5000 psig. Seals within the valve body consisted of polymers suitable for use in high pressure hydrogen applications. Despite the appearance of the nozzle in Figure 16, the LW 5000 did not feature a bulkhead mount. Such a feature would have been used to provide structural rigidity to the
refueling receptacle when attaching the nozzle. To compensate for the lack of bulkhead mount, an additional support structure had to be designed and fabricated that implemented a bulkhead mount tube union in close proximity to the receptacle. This support structure is illustrated in Figure 17 and Figure 18.

**Figure 17.** Fill nozzle front oblique view.

**Figure 18.** Fill nozzle rear oblique view.
Hydrogen Direct Cylinder Injection System

The original port injection system was replaced by a custom designed and custom fabricated direct cylinder hydrogen injection system. Injection ports in the intake manifold were fitted with custom blow off valves. In the event of ignition in the intake manifold, these valves will open and prevent the resulting pressure rise from damaging any part of the intake manifold or vital components such as the manifold absolute pressure sensor. The replacement injectors are a hybrid between a spark plug and a gaseous fuel injector. Each injector is equipped its own internal check valve and utilizes appropriate grades of ceramic to electrically isolate major metal components. A cutaway view of one injector used in this system is illustrated in Figure 19. The injector was designed by Ronald Fifield, a graduate student at the University of Nevada at Las Vegas. A piping and instrumentation diagram of the injection plumbing system is given in Figure 20.

Figure 19. A hydrogen direct cylinder injector is illustrated in this figure. It utilizes a check valve to isolate hydrogen flow during the expansion stroke. This figure illustrates the use of ceramic in electrically isolating major electrical components. Figure courtesy of R. Fifield [2007].

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Figure 20. The above figure is a piping and instrumentation diagram of the plumbing system employed on Ford F-250.

Instrumentation

Instrumentation on the vehicle was divided into the categories of primary and secondary systems. Primary instrumentation comprised the collection of devices necessary for normal operation of the vehicle. Included in this system were the line pressure transducer, digital display meter, solenoid shutoff valve, mechanical pressure gauges, and hydrogen leak detection system. The pressure transducer was a Class 1, Division 1, IS Groups C and D certified for use in intrinsically safe areas. It operated using a stainless steel diaphragm in conjunction with a strain gauge. Its voltage output
was configured to be 1 to 5 VDC. It was installed in a female branch tee to sense line
pressure. Its port connection was a male pipe thread, as this was the only type of
connection available. The display meter to which it connected accepted a 1 to 5 VDC
input. Specific technical details for the transducer and the display can be found in the
Appendix.

A hydrogen leak detection system has been added to prevent operation of the
vehicle in the event that a leak develops. This system consists of three catalytic
hydrogen sensors connected in parallel. A wiring schematic is given in. Each sensor had
a detection resolution of 100 ppm, and set points calibrated at ten percent and twenty
percent of the lower flammability limit (LFL) for hydrogen in air. Twenty percent of the
hydrogen LFL corresponded to a concentration of 8000 ppm. A frequently occurring
problem with sensors of this type was their tendency to be set off by exhaust gases from
gasoline and diesel powered vehicles. To negate this tendency, each sensor was
equipped with a filter that removed volatile organic gases (VOCs) from a given gas
sample. Activation of each sensor took place in two stages according to the
concentration of hydrogen in the air. First stage activation took place at 4000 ppm and
included an audible alarm and change in color of an LED on the front face of the sensor
from green to yellow. Second stage activation occurred at a concentration of 8000 ppm
and activated a normally-open relay internal to the sensor. Specific details on the wiring
configuration of these sensors will be discussed in a later section. Input voltage to the
device could range from 5 to 40 VDC. A 0 to 3 VDC proportional output voltage signal
allowed concentrations of hydrogen to be sensed real-time. This sensor is illustrated
below in Figure 22. Each of the sensors in the bed was encased in a shroud intended to
increase the concentration of hydrogen passing in the vicinity of the sensor. This shroud is illustrated in Figure 21.

Pressure gauges employed in the system were capable of reading up to 6000 psig, which is in agreement with the previously stated applicable NFPA standard. Each gauge used a welded bourdon tube and bottom-mount pipe threads. The opening of each gauge had an effective diameter of less than 0.055 in, as specified in NFPA 52, item 5.6.2. To improve accuracy, each gauge was configured to be glycerin filled.

![Figure 21](image1.png)

**Figure 21.** Shroud placed around each sensor in the bed of the F250.

![Figure 22](image2.png)

**Figure 22.** Hydrogen sensor produced by Neodym. Two of these sensors were placed at specific locations in the truck bed and one was placed in the engine compartment.
**Ignition and Power System**

Factory power systems consisting of the alternator and battery were replaced by a Ballard 1.2 kW hydrogen fuel cell and two super-capacitors. The fuel cell was selected to have a high enough power output that it could substitute the alternator and battery during cranking and running. A bank of two super capacitors was capable of supporting the power requirements of the vehicle electrical systems and instrumentation while the fuel cell completes its warm-up cycle. The fuel cell and super capacitors are illustrated in Figure 23. Once the fuel cell has completed its warm up cycle, it is capable of providing adequate power to the vehicle instrumentation and electronics. While this system could also be equipped with a power inverter for devices that require AC power, there were no plans to implement such a feature.

![Figure 23. The Ballard fuel cell and super capacitors are connected to an improvised load bank. In the lower right, two batteries connected in series supplied power to the fuel cell electronics during startup. Photograph courtesy of R. Hurt.](image)

The Ballard fuel cell that constitutes the energy generation element of the APU does not store water in the vicinity of the membranes. This feature is common among Ballard
fuel cells and is a major distinguishing feature when comparing Ballard fuel cells to others currently found in industry. A majority of fuel cell power units found in industry require a certain amount of water to remain on the stack membranes to keep the membranes hydrated. Ballard fuel cells negate this requirement through the use of a patented membrane material that does not require membrane hydration during periods of non-use, which indirectly eliminates the need for a reservoir. Included in Figure 23 is the load bank used in preliminary testing to validate the power system design. This load bank was a DC resistive type load bank configured to incrementally increase the load by closing consecutive blade type switches. Voltage and current were measured instantaneously as load on the fuel cell was increased incrementally. The bank of super capacitors complementing the fuel cell was produced in Korea and stores a charge sufficient to power the vehicle electrical and ignition systems during fuel cell warm-up and power the starter motor for at least two minutes. Both the vehicle electrical system and the ignition system have been outfitted with a time circuit that delays engine shutdown for five seconds.

Figure 24. This is a timing circuit produced by the Altronix Company. Its timing scale can be switched to minutes or seconds.
The circuit illustrated in Figure 24 was installed in the vehicle as a method for reducing the likelihood of backfire during starting. Experience with the Polaris Ranger highlighted the tendency of the solenoid valve to leak hydrogen a rate sufficient to slightly displace a downstream check valve and leak hydrogen into the cylinder. This vented hydrogen was occasionally able to ignite when entering the exhaust and produce a backfire of considerable magnitude. This phenomenon was negated by the introduction of the timing circuit illustrated in Figure 24. When placed in series with the ignition key switch, the timing circuit delays ignition system shutdown for approximately five seconds. Hydrogen remaining in the cylinder was ignited and kept the engine running for approximately one second after the key switch had been set to the “off” position. A similar scheme was employed on the Ford, but without a completed set of injectors, the effectiveness its implementation could not be determined.

*Emergency Venting Scenarios*

In accordance with criteria set forth in NFPA 52, vent lines were terminated in such a manner as to avoid impingement on any part of the fuel system and to minimize the effects of high temperature and contact with the escaping gas on personnel, adjacent structures and ignition sources in the vicinity of the vehicle during a venting incident. Vent line termination points were located in close proximity to the vehicle cab and as laterally central as available space allowed. Additionally, termination points were pointed slightly away from the cab and toward the center of the bed. This orientation of the termination points directed any vented gases away from personnel depressurizing the fuel system, as the location of the manual venting valve required service personnel to be in close proximity to the termination.
CHAPTER 5

ENGINE PROGRAMMING

At the time this thesis was written, the fuel injection system for the truck had not yet been fabricated. It is for this reason that this thesis will not provide any experimental results on engine performance. Numbers and figures presented in this chapter are based on theory and simulation and are representative of parameters by which engine performance is typically characterized. Modern ECM's actively control inputs to an engine based on feedback values coming from sensors strategically located on the engine. Inputs to a given engine include fuel delivered and ignition timing, while measured outputs used for feedback control include manifold pressure, manifold air temperature, coolant temperature and exhaust oxygen content.

The ignition timing programmed into the ECM was presumably based on the flame speed of CNG. The ignition timing programmed into the ECM at the factory was obtained through an aftermarket programming module produced by the company SCT. Ignition timing is determined as an optimum between the maximum cylinder pressures as determined by ignition timing and the maximum torque as determined by engine geometry. Considering the relatively high flame speed of hydrogen, ignition timing optimized for the highest cylinder pressure possible would be from zero to five degrees before top dead center (BTDC). When engine geometry is taken into account, however, this ignition timing produces a high pressure on the face of the piston when the
connector rod and crank offset are nearly collinear. Such a scenario produces no torque about the crank shaft and the engine produces no power. Allowing the crank shaft to move into a position where torque production is possible decreases the maximum in-cylinder pressure by increasing the volume in which combustion takes place. Ignition timing varies in any electronically controlled ignition scheme with engine VE and RPM. Based on experience from engine tuning on the Polaris Ranger, the goal of this vehicle is expected to be low emissions, as opposed to high horsepower. Ignition timing with the end goal of low emissions requires advancing ignition timing beyond that for increased power output.

*Ford ECM Programming*

Reprogramming the Ford ECM will be performed using the Strategy Flash aftermarket reprogramming module produced by SCT. The device is illustrated in Figure 25. This particular make and model was selected for its full adjustability with regard to spark and fuel timing as well as the scope of variables it is capable of changing. Other models available in industry are typically designed for reprogramming a gasoline powered engine, which means the range of variation of each of the controlling variables is small. This particular module is dedicated. Once it is connected to the ECM of a vehicle, it stores data unique to that ECM and cannot be connected to the ECM of another vehicle. Its memory can be reset, but resetting erases all stored parameter values.

Software used to interface with the module is also produced by SCT. This software, Advantage 3, allows for full adjustment of all variables programmed into the ECM. Variables stored in the ECM are arranged in the graphical user interface in a tree format.
Reprogramming that will take place using the above mentioned software and module will be difficult, as modern ECM’s use greater than three measured engine output variables in their feedback loops. These multiple measured outputs are used to adjust ignition timing and fuel pulse width in order to keep the engine running in a range of parameters that affect the greatest positive impact on emissions. The primary difficulty in reprogramming this ECM is anticipated to be the lack of a clear map of all feedback variables and how each variable effects fuel pulse width and ignition timing. A fuel pulse and ignition timing map will be presented based on variables whose influence on output is known. Variables whose influence is not known will have to be determined and adjusted based on experimental iteration.

![Image](image-url)

**Figure 25.** The ECM reprogramming module produced by SCT is illustrated above.

At the time this thesis was written, the truck was not in a state suitable for testing. Relationships and concepts presented in this section represent a theoretical approach to
tuning the engine on this vehicle. Several models found in recent publications will be presented in this section that have been used by the respective authors with varying degrees of success, however each of these models requires experimental calibration of specific variables and experimental determination of coefficients. Principal among the variables that must be determined experimentally are intake manifold flow characteristics. Several models have considered air flowing into the intake through the throttle valve to be an isentropic expansion process. Aquino [1981] and Fiaschetti et al., in separate works cited in Franchek et al [2006], derived the following mass balance relationship for air flowing through a given intake manifold,

$$\frac{dM}{dt} = \frac{dm_{th}}{dt} - \frac{dm_{up}}{dt}$$

(6)

where $M$ is the mass of air in the intake, $m_{th}$ is the mass of air in the vicinity of the throttle plate and $m_{up}$ is the mass of air in the vicinity of the intake valve. For a given volumetric efficiency, $\eta_v$, the air mass flow rate can be obtained from the following equation:

$$\eta_v = \frac{2 \cdot \frac{dm_a}{dt} \cdot R \cdot T_a}{P_m \cdot V_d \cdot N \cdot M_a}$$

(7)

Considering the ideal gas relationship for a flow system at constant volume, Franchek et al [2006] and Nicolao et al [1996] derived a first order differential equation that accurately describes the flow dynamics of the intake manifold in response to
disturbances such as change in throttle plate angle and crank shaft speed. This equation
was of the form,

$$\frac{d p_m}{dt} = \frac{-N}{120} \frac{V_d}{V} \eta V \cdot p_m + \frac{R \cdot T_m}{V} \frac{dm_{th}}{dt}$$

(8)

where $N$ is the engine speed in RPM, $V_d$ is the displacement volume, $V$ is the volume of
the intake manifold, $\eta V$ is the volumetric efficiency, $p_m$ is the manifold pressure and $T_m$
is the manifold temperature. The above equation would be implemented in a predictive
control scheme to adjust fuel injection pulses. Nicolao [1996] proposed the following
equation for black box identification purposes,

$$\eta V = \frac{120}{N} \frac{R \cdot T_m}{V_d p_m M_{H2}} \cdot \lambda \cdot \alpha_s \cdot \frac{dm_f}{dt}$$

(9)

In the above equation, $\lambda$ is the air-equivalence ratio and $\alpha_s$ is the stoichiometric air fuel
ratio. Based on variables found in the Ford ECM, the above equation would apply well,
as $\eta V$ is used in the ECM to indicate engine load and $\lambda$ is used as a corrector for
adjusting fuel injection pulses according to RPM and load. In equation (9), $N$, $T_m$, $p_m$
and $\lambda$ are all measured variables while $\eta V$ is a calculated variable and the fuel mass flow
rate is a resulting output. Correct determination of $\eta V$ was approximated by Franchek et
al [2006] as
E in equation (10) is an experimentally determined constant.

Intake manifold air flow was calculated from the existing CNG fuel tables. Fuel quantities in the programmed table were given in terms of \( \lambda (=1/\varphi) \), which was used with the programmed stoichiometric air-fuel ratio to obtain a quantity of air. The stoichiometric air-fuel ratio for CNG is approximately 17.2 to 1, while the programmed stoichiometric air fuel ratio for the original CNG fuel tables was 16.75 to 1. This slightly rich mixture could have been a strategy for improving emissions. Fuel tables for hydrogen flow were determined from, which provided the following relation between air mass flow rate, volumetric efficiency (\( \eta_V \)), and engine speed:

\[
\eta_V = \frac{2 \cdot \frac{dm_a}{dt}}{\rho_a \cdot V_d \cdot N}
\]  

(11)

The ECM on the Ford computer uses \( \eta_V \) to indicate load on the engine. The Ford ECM uses a modified version of the above equation that incorporates the target air fuel ratio and measured air equivalence ratio, \( \lambda \). Nicolao et al [1996] gave the following form for this equation:
\[
\eta_V = \frac{120 \cdot \frac{R \cdot T_m}{N} \cdot \frac{\lambda \cdot \alpha_s}{V_d \cdot p_m \cdot M_{H2}}}{\int \frac{dm_f}{dt}}
\]  \hspace{1cm} (12)

The above equation allows for the calculation of \( \eta_V \) based on measurable quantities such as air equivalence ratio, manifold temperature and manifold absolute pressure and on a controllable quantity, the fuel mass flow rate. Using ranges of volumetric efficiency and engine RPM from the original files found on the engine computer, equation 12 was solved for the air mass flow rate and used to generate the surface plots given in Figure 27, Figure 28 and Figure 29. The air mass flow rate at calculated for a given RPM and VE was taken as the maximum over the course of one cycle. Valve lift measurements were taken every ten degrees of crank rotation. Results from these measurements are summarized in Figure 26. This intake flow rate was then scaled to the intake cam profile obtained from measurements taken from the engine. The peak valve lift illustrated in Figure 26 was assumed to correspond to the maximum air mass flow rate. Additionally, data from Figure 26 was used to calculate an intake stroke time duration. A total mass of air inducted over one cycle was obtained by solving equation (12) and integrating it using trapezoidal rule. Code used to generate Figure 27 through Figure 29 can be found in the appendix.
Figure 26. The above figure illustrates the measurements taken to determine intake valve lift profile as a function of crank angle.

Figure 27. Air mass flow rate in pounds per second as a function of RPM and VE.
Figure 28. The above figure represents the mass of air inducted per cycle in pounds. A noteworthy region on this plot is the area of low volumetric efficiency and high RPM.

Figure 29. The above figure represents the mass of hydrogen inducted per cycle in pounds. This model took into account friction losses through the intake valve and incorporated measurements taken on the intake valve corrected for rated intake valve lift.
Each point in the curve illustrated in Figure 26 was scaled to the maximum valve lift. Air passing through a valve does not flow through the largest area possible, but instead flows through an area smaller than what is available. This phenomenon is typically quantified by a valve flow coefficient. Algieri [2006], citing Heywood [1998], used the following expression for the flow coefficient:

\[
C_f = \frac{\frac{dm}{dt}}{\frac{dm_{\text{max}}}{dt}}
\]  

(13)

where \(\frac{dm}{dt}\) is a reference mass flow rate determined by isentropic flow relationships. Experimental results from Algieri [2006] yielded a flow coefficient of 0.46 for the dimensionless valve lift, \(L_v/D_v\), determined from intake valve dimensions given in the Ford F-250 workshop manual. In the case of subsonic flow, if \(T_0\) and \(p_0\) are the ambient temperature and pressure, respectively, \(\gamma\) is the ratio of specific heats and \(p_c\) is the cylinder pressure, the reference air mass flow rate takes on the following form [Algieri, 2006]:

\[
\frac{dm}{dt} = A_{\text{ref}} \frac{P_0}{R M T_0} \left( \frac{p_c}{p_0} \right)^{\frac{1}{2}} \left[ 1 - \left( \frac{p_c}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right]^\frac{1}{2}
\]

(14)

where \(A_{\text{ref}}\) is in reference to the intake valve area given in Algieri [2006] of the form.
\[ A_{\text{ref}} = \frac{\pi}{4} D_v^2 \]  \hspace{1cm} (15)

In the flow is choked (sonic), the subsonic flow relation reduces to the following given in Algieri [2006]:

\[ \frac{dm}{dt} = A_{\text{ref}} \frac{p_0}{\sqrt{\frac{R}{M}} T_0} \frac{1}{\gamma} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \]  \hspace{1cm} (16)

Since the above equations for mass flow rate are highly dependent upon flow velocity, a reference velocity and corresponding Mach number must be calculated to determine which relationship to use. This reference velocity can be obtained from the isentropic relation for flow from a converging nozzle emptying into a plenum [Algieri, 2006]:

\[ v_0 = \sqrt{\frac{2 \gamma}{\gamma - 1} \frac{p_0}{\rho_0} \left[ 1 - \left( \frac{p_c}{p_0} \right)^{\gamma} \right]} \]  \hspace{1cm} (17)

\( p_c \) in equation 17 represents in-cylinder pressure during the intake stroke. This quantity will have to be extrapolated based on past experience with the Polaris Ranger.

Considering the definition of the speed of sound, \( c \), in air,

\[ c = \sqrt{\frac{R}{M} T_0} \]  \hspace{1cm} (18)
the Mach number for the flow can be calculated as,

\[ M = \frac{v_0}{c} \]  

(19)

Scenarios involving manifold pressures at approximately 53% of the ambient pressure exemplify choked flow regimes, so it is these scenarios that must be used to calculate a reference velocity. Past work done on a Polaris Ranger demonstrated that manifold absolute pressure as low as 8.8 PSIA was possible during normal operating conditions. Taking ambient pressure to be 14.7 PSIA, the ratio of ambient pressure to manifold pressure is 0.6, which is greater than 0.53 and would indicate that the flow traveling through the intake manifold is not choked (subsonic). Nevertheless, it is still possible that air traveling past the intake valve exhibits choked characteristics. Due to a lack of experimental data, flow characteristics through the intake valve could not be verified. For more accurate tuning and system identification purposes, any assumed model will have to be improved iteratively.

Engine testing and tuning will take place on a chassis-mount dynamometer provided by the Fleet Services division of the Las Vegas Valley Water District. This method of dynamometer tuning offers the benefit of accounting for the load of the transmission on the engine during the tuning phase. Past experience with the Polaris Ranger has demonstrated the effects of a transmission on available power at the rear axle and starting can be significant. Past conversations with Garrett Beauregard of EV Infrastructure have corroborated this experience, for in the case of hydrogen as an IC engine fuel, satisfactory engine-mount dynamometer tuning can be made null and void
when the engine is reinstalled in the vehicle. Chassis-mount tuning offers the
disadvantage of competing with programmed transmission shift points. A given modern
automotive transmission is controlled by the ECM and programmed to shift at specific
RPM. In tuning an engine for use with a new fuel, a problem frequently encountered is
transmission shifting during a tuning session. The shift changes the load on the engine,
and can interfere with the test results. New transmission shift points should be
determined iteratively in field testing after a suitable set of fuel and ignition timing
tables have been obtained.
CHAPTER 6

CONCLUSIONS

A Ford F-250 vehicle originally designed to burn CNG was converted to run on hydrogen. The factory configuration was documented and presented. Design specifications were given and correlated with manufacturers’ specifications and ratings. Designs for component mounting were presented and corresponding factors of safety verified. Factors of safety for vent lines pressurized to a projected pressure compared to the rated working pressure of the tube were given. Applicable standards were stated and demonstrated to be satisfied. Various methods for engine tuning were presented, but ultimately each method presented requires experimental validation. Selected methods were used to produce some initial fuel tables, but even these tables will require an iterative refinement type of approach. Certain flow characteristics of the hydrogen spark plug-fuel injector had to be assumed, as experimental data was not available when the fuel tables were formed. Flow data was taken from flow tests on the poppet valve assembly and taken to be representative of the flow characteristics of the injector assembly. A hydrogen PEM fuel cell was installed and validation was performed. Results of this testing were given and demonstrated capability of the fuel cell to provide power to the vehicle electronic system and ignition system. The fuel system incorporated a set of devices that have the potential to greatly simplify future hydrogen
vehicle conversions. Each of these devices consolidates a fuel injector and spark plug such that the entire assembly will fit into an existing spark plug port.

A review of current literature was given. Time required for hydrogen powered vehicles to be economically viable is heavily dependent on economic factors, some of which include consumer willingness to pay higher prices for environmental incentives (i.e. carbon emissions reduction). While emissions reduction may be an attractive prospect for consumers, measurable reductions as a result of widespread zero-emissions vehicle use will come long after adequate market penetration has occurred. Obstacles to hydrogen vehicle penetration can be overcome through by factors that include, but are not limited to, government and private sector subsidy and consumer willingness to purchase higher priced vehicles with little or no indication of short-term financial return.
**APPENDIX**

**Manufacturers’ Technical Data Sheets**

Swagelok Tubing Technical Data

4 Tubing Data

**Suggested Allowable Working Pressure for Stainless Steel Tubing**

Allowable working pressures are calculated from an S value of 2000 psi (1370 kPa) for ASTM A269 tubing at -20 to 100°F (-28 to 37°C), as listed in ASME B31.3, except as noted. Multiply stainless steel rating by 0.94 for working pressure in accordance with ASME B31.1.

### For Welded Tubing

For welded and drawn tubing, a derating factor must be applied for weld integrity:
- For double-welded tubing, multiply pressure rating by 0.85
- For single-welded tubing, multiply pressure rating by 0.80

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### For Welded Tubing

For welded and drawn tubing, a derating factor must be applied for weld integrity:
- For double-welded tubing, multiply pressure rating by 0.85
- For single-welded tubing, multiply pressure rating by 0.80

### Suggested Ordering Information

Fully annealed, high-quality (Type 304, 316, etc.) seamless or welded and drawn stainless steel hydraulic tubing ASTM A269 or A213, or equivalent, hardness 80 HRB (180 HV) or less. Tubing to be free of scratches, suitable for bending and flaring.

Note: Certain austenitic stainless tubing has an allowable ovality tolerance double the OD tolerance and may not fit into Swagelok precision tube fittings.

**Table 4—Metric Stainless Steel Seamless Tubing**

Allowable working pressures are based on equations from ASME B31.3 for EN ISO 1127 tubing (D4. T4 tolerance for 3 to 12 mm; D4. T3 tolerance for 14 to 50 mm), using a stress value of 1370 bar (20000 psi) and tensile strength of 5170 bar (75000 psi), except as noted. Multiply stainless steel rating by 0.94 for working pressure in accordance with ASME B31.1.

For Welded Tubing

For welded and drawn tubing, a derating factor must be applied for weld integrity:
- For double-welded tubing, multiply pressure rating by 0.85
- For single-welded tubing, multiply pressure rating by 0.80

### Suggested Ordering Information

Fully annealed, high-quality (Type 304, 316, etc.) stainless steel tubing to EN ISO 1127 or equivalent, hardness 100 HRB (180 HV) or less. Tubing to be free of scratches, suitable for bending and flaring.

**Swagelok**

Highlighted are the pressure ratings for tubing used in this system.
**Tube to Male Pipe**

**FBZ, MSCN**

**NPT Male Connector**

*For fractional tube*

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<td>1/8</td>
<td>1/8</td>
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</tr>
<tr>
<td>3/8 FBZ</td>
<td>1/16</td>
<td>1/16</td>
<td>1/32</td>
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</tr>
<tr>
<td>1/4 FBZ</td>
<td>1/16</td>
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<tr>
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</tr>
</tbody>
</table>

---

**Color Coding**

For easy reference, tube heads are color coded as follows:

- **Fractional**
  - All tubes: Blue
- **Metric**
  - All tubes: Green

---

Parker-Hannifin A-Lok Pipe to Tube adapter Fittings
# Tube to Male Pipe

**FBZ, MSCN NPT Male Connector**

For fractional tube

<table>
<thead>
<tr>
<th>Size</th>
<th>A</th>
<th>B</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
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</thead>
<tbody>
<tr>
<td>1/8</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
<td>3/8</td>
<td>5/32</td>
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<td>1/8</td>
</tr>
<tr>
<td>5/32</td>
<td>1/32</td>
<td>1/16</td>
<td>1/4</td>
<td>3/16</td>
<td>7/32</td>
<td>1/8</td>
<td>1/16</td>
</tr>
<tr>
<td>1/4</td>
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<td>1/8</td>
<td>3/16</td>
<td>7/32</td>
<td>1/4</td>
<td>1/8</td>
</tr>
</tbody>
</table>

**Color Coding**

For easy reference, table heads are color indicated as follows:

- **Fractional**
- **Metric**

---

Parker-Hannifin A-Lok Union Tube Fittings

---

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# Tube to Tube Unions

## HBZ, SC Union

For fractional tube

<table>
<thead>
<tr>
<th>CPT PART NO.</th>
<th>A-LOC PART NO.</th>
<th>INTERCHANGES WITH</th>
<th>TUBE O.D.</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>W H.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1 HBZ</td>
<td>10SC1</td>
<td>130-6</td>
<td>1/16</td>
<td>.99</td>
<td>.43</td>
<td>.69</td>
<td>5/16</td>
</tr>
<tr>
<td>2-2 HBZ</td>
<td>20SC2</td>
<td>230-6</td>
<td>1/16</td>
<td>1.39</td>
<td>.80</td>
<td>.98</td>
<td>7/16</td>
</tr>
<tr>
<td>3-3 HBZ</td>
<td>30SC3</td>
<td>330-6</td>
<td>1/4</td>
<td>1.82</td>
<td>.70</td>
<td>1.63</td>
<td>12</td>
</tr>
<tr>
<td>5-5 HBZ</td>
<td>50SC5</td>
<td>530-6</td>
<td>5/16</td>
<td>1.70</td>
<td>.73</td>
<td>1.31</td>
<td>6/16</td>
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<td>6-6 HBZ</td>
<td>60SC6</td>
<td>630-6</td>
<td>7/16</td>
<td>1.77</td>
<td>.76</td>
<td>1.19</td>
<td>5/8</td>
</tr>
<tr>
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<td>80SC8</td>
<td>830-6</td>
<td>1/2</td>
<td>2.02</td>
<td>.87</td>
<td>1.22</td>
<td>10/16</td>
</tr>
<tr>
<td>10-10 HBZ</td>
<td>100SC10</td>
<td>1030-6</td>
<td>9/16</td>
<td>2.65</td>
<td>.87</td>
<td>1.25</td>
<td>15/16</td>
</tr>
<tr>
<td>12-12 HBZ</td>
<td>120SC12</td>
<td>1230-6</td>
<td>3/4</td>
<td>3.11</td>
<td>.87</td>
<td>1.31</td>
<td>1-1/16</td>
</tr>
<tr>
<td>16-16 HBZ</td>
<td>160SC16</td>
<td>1630-6</td>
<td>3/4</td>
<td>3.17</td>
<td>1.65</td>
<td>1.59</td>
<td>1-3/8</td>
</tr>
<tr>
<td>20-20 HBZ</td>
<td>200SC20</td>
<td>2030-6</td>
<td>1-1/4</td>
<td>3.61</td>
<td>1.52</td>
<td>1.89</td>
<td>1-3/4</td>
</tr>
<tr>
<td>24-24 HBZ</td>
<td>240SC24</td>
<td>2430-6</td>
<td>1-1/2</td>
<td>4.23</td>
<td>1.77</td>
<td>2.11</td>
<td>2-1/16</td>
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</tbody>
</table>

NOTE: A and C dimensions are typical fingeright. Dimensions for reference only, subject to change.

## HBZ, SCM Union

For metric tube

<table>
<thead>
<tr>
<th>CPT PART NO.</th>
<th>A-LOC PART NO.</th>
<th>INTERCHANGES WITH</th>
<th>TUBE O.D.</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>W H.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBZ 2-2 SCM</td>
<td>2SCM2</td>
<td>2MC-6</td>
<td>6</td>
<td>30.9</td>
<td>15.3</td>
<td>22.4</td>
<td>12.0</td>
</tr>
<tr>
<td>HBZ 3-3 SCM</td>
<td>3SCM3</td>
<td>3MC-6</td>
<td>6</td>
<td>37.6</td>
<td>16.1</td>
<td>24.2</td>
<td>12.0</td>
</tr>
<tr>
<td>HBZ 4-4 SCM</td>
<td>4SCM4</td>
<td>4MC-6</td>
<td>6</td>
<td>43.2</td>
<td>17.7</td>
<td>26.6</td>
<td>14.0</td>
</tr>
<tr>
<td>HBZ 6-6 SCM</td>
<td>6SCM6</td>
<td>6MC-6</td>
<td>6</td>
<td>48.3</td>
<td>19.6</td>
<td>28.2</td>
<td>16.0</td>
</tr>
<tr>
<td>HBZ 10-10 SCM</td>
<td>10SCM10</td>
<td>10MC-6</td>
<td>10</td>
<td>62.2</td>
<td>19.5</td>
<td>31.0</td>
<td>18.0</td>
</tr>
<tr>
<td>HBZ 12-12 SCM</td>
<td>12SCM12</td>
<td>12MC-6</td>
<td>12</td>
<td>67.2</td>
<td>22.0</td>
<td>31.0</td>
<td>22.0</td>
</tr>
<tr>
<td>HBZ 16-16 SCM</td>
<td>16SCM16</td>
<td>16MC-6</td>
<td>16</td>
<td>82.0</td>
<td>22.0</td>
<td>31.0</td>
<td>24.0</td>
</tr>
<tr>
<td>HBZ 20-20 SCM</td>
<td>20SCM20</td>
<td>20MC-6</td>
<td>20</td>
<td>97.0</td>
<td>22.0</td>
<td>31.0</td>
<td>24.0</td>
</tr>
<tr>
<td>HBZ 24-24 SCM</td>
<td>24SCM24</td>
<td>24MC-6</td>
<td>24</td>
<td>106.5</td>
<td>22.0</td>
<td>31.0</td>
<td>24.0</td>
</tr>
</tbody>
</table>

NOTE: A and C dimensions are typical fingeright. Dimensions for reference only, subject to change.

## Color Coding

For easy reference, table heads are color indicated as follows:

- **fractional**
- **metric**

---

Parker-Hannifin A-Lok Tube Unions

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### HBZ, CU Conversion Union
**For metric tube**

|------------------------|---------|---------|----------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|

### HBZ, RU Reducing Union
**For fractional tube**

|----------------|---------|---------|----------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|

### HBZ, RUM Reducing Union
**For metric tube**

|----------------|---------|---------|----------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|

### Notes:
- A, C, and D dimensions are typical for each size.
- Dimensions are for reference only, subject to change.

Parker-Hannifin A-Lok Tube End Reducer

---

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### Port Connectors

**TRBZ, TUR Tube End Reducer**

**For fractional tube**

<table>
<thead>
<tr>
<th>PART #</th>
<th>A-LINE#</th>
<th>SIZE CHARTED WITH</th>
<th>TUBE END REDUCER</th>
<th>TUBE O.D.</th>
<th>TUBE O.D. W/HOLE</th>
<th>D</th>
<th>E</th>
<th>W</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1 TRBZ</td>
<td>2TR21</td>
<td>100-R-2</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
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<tr>
<td>3-1 TRBZ</td>
<td>3TR21</td>
<td>100-R-3</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>4-1 TRBZ</td>
<td>4TR21</td>
<td>100-R-4</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>5-1 TRBZ</td>
<td>5TR21</td>
<td>100-R-5</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>6-1 TRBZ</td>
<td>6TR21</td>
<td>100-R-6</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>7-1 TRBZ</td>
<td>7TR21</td>
<td>100-R-7</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>8-1 TRBZ</td>
<td>8TR21</td>
<td>100-R-8</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
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<tr>
<td>9-1 TRBZ</td>
<td>9TR21</td>
<td>100-R-9</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>10-1 TRBZ</td>
<td>10TR21</td>
<td>100-R-10</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>11-1 TRBZ</td>
<td>11TR21</td>
<td>100-R-11</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>12-1 TRBZ</td>
<td>12TR21</td>
<td>100-R-12</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>13-1 TRBZ</td>
<td>13TR21</td>
<td>100-R-13</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
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<tr>
<td>14-1 TRBZ</td>
<td>14TR21</td>
<td>100-R-14</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>15-1 TRBZ</td>
<td>15TR21</td>
<td>100-R-15</td>
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<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>16-1 TRBZ</td>
<td>16TR21</td>
<td>100-R-16</td>
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<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
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<tr>
<td>17-1 TRBZ</td>
<td>17TR21</td>
<td>100-R-17</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
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<td>18TR21</td>
<td>100-R-18</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>19-1 TRBZ</td>
<td>19TR21</td>
<td>100-R-19</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
<tr>
<td>20-1 TRBZ</td>
<td>20TR21</td>
<td>100-R-20</td>
<td>1 1/8</td>
<td>1 1/8</td>
<td>1 1/4</td>
<td>.25</td>
<td>.63</td>
<td>.12</td>
<td>TRBZ.TUR</td>
</tr>
</tbody>
</table>

**NOTE:** A and C dimensions are typical lingot light. Dimensions for reference only, subject to change. Size 4 and above tube stub is pre-grooved as standard. Generics not grooved can be ordered through Quick Response Department.

- Size 1, 2, and 5 do not require a groove.
- Add -Z for assembly of nuts and ferrules on the tube stub end.
- Size 20, 24 require additional lubrication prior to assembly.

### Color Coding

For easy reference, table heads are color indicated as follows:

- fractional
- metric

---

Parker-Hannifin A-Lok Bulkhead Union Fittings

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### Tube to Tube Unions

**WBZ, BC**

**Bulkhead Union**

*For fractional tube*

<table>
<thead>
<tr>
<th>PART NO.</th>
<th>SIZE</th>
<th>NUT-</th>
<th>TUBE</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>F</th>
<th>L</th>
<th>W</th>
<th>HEX</th>
<th>GRILL SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1WBZ</td>
<td>1BC1</td>
<td>10C-1</td>
<td>1/16</td>
<td>1.25</td>
<td>.43</td>
<td>.34</td>
<td>.62</td>
<td>.26</td>
<td>.35</td>
<td>5/16</td>
<td>19/64 1/16</td>
</tr>
<tr>
<td>2-2WBZ</td>
<td>2BC2</td>
<td>20C-2</td>
<td>1/2</td>
<td>2.50</td>
<td>.93</td>
<td>1.36</td>
<td>1.23</td>
<td>.64</td>
<td>.37</td>
<td>7/32</td>
<td>39/64 1/2</td>
</tr>
<tr>
<td>3-3WBZ</td>
<td>3BC3</td>
<td>30C-3</td>
<td>1/4</td>
<td>1.75</td>
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<td>.35</td>
<td>.63</td>
<td>.28</td>
<td>.41</td>
<td>1/4</td>
<td>37/64 1/2</td>
</tr>
<tr>
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<td>4BC4</td>
<td>40C-4</td>
<td>1/2</td>
<td>2.00</td>
<td>.75</td>
<td>.44</td>
<td>.62</td>
<td>.25</td>
<td>.41</td>
<td>5/32</td>
<td>29/64 1/2</td>
</tr>
</tbody>
</table>

### WBZ, BCM

**Bulkhead Union**

*For metric tube*

<table>
<thead>
<tr>
<th>PART NO.</th>
<th>SIZE</th>
<th>NUT-</th>
<th>TUBE</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>F</th>
<th>L</th>
<th>W</th>
<th>HEX</th>
<th>GRILL SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1WBZ</td>
<td>1BCM1</td>
<td>10C-1</td>
<td>1/16</td>
<td>1.25</td>
<td>.43</td>
<td>.34</td>
<td>.62</td>
<td>.26</td>
<td>.35</td>
<td>5/16</td>
<td>19/64 1/16</td>
</tr>
<tr>
<td>2-2WBZ</td>
<td>2BCM2</td>
<td>20C-2</td>
<td>1/2</td>
<td>2.50</td>
<td>.93</td>
<td>1.36</td>
<td>1.23</td>
<td>.64</td>
<td>.37</td>
<td>7/32</td>
<td>39/64 1/2</td>
</tr>
<tr>
<td>3-3WBZ</td>
<td>3BCM3</td>
<td>30C-3</td>
<td>1/4</td>
<td>1.75</td>
<td>.47</td>
<td>.35</td>
<td>.63</td>
<td>.28</td>
<td>.41</td>
<td>1/4</td>
<td>37/64 1/2</td>
</tr>
<tr>
<td>4-4WBZ</td>
<td>4BCM4</td>
<td>40C-4</td>
<td>1/2</td>
<td>2.00</td>
<td>.75</td>
<td>.44</td>
<td>.62</td>
<td>.25</td>
<td>.41</td>
<td>5/32</td>
<td>29/64 1/2</td>
</tr>
</tbody>
</table>

**NOTE:** For reducer sizes call out sheet and list. A, C, and C~ dimensions are typical finishing. For replacement bulkhead nut, see Page 75, Part WI-2.

### Color Coding

For easy reference, table heads are color indicated as follows:

- Fractional: **Red**
- Metric: **Blue**

---

**Parker-Hannfin A-Lok Branch Tee**
# Tube to Female Pipe

**OBZ, FBTN**  
NPT Female  
Branch Tee  
*For fractional tube*

**OBZ, FBTN**  
NPT Female  
Branch Tee  
*For metric tube*

## Table: Dimensions

<table>
<thead>
<tr>
<th>CPP Part No.</th>
<th>A-Lok Part No.</th>
<th>NPT Threads</th>
<th>Tube O.D.</th>
<th>Miliemes</th>
<th>Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBZ 6-6-1-8</td>
<td>MFPTB18N</td>
<td>5MO-3TTF</td>
<td>6</td>
<td>53.9</td>
<td>2.1</td>
</tr>
<tr>
<td>OBZ 6-6-1-4</td>
<td>MFPTB14N</td>
<td>5MO-3TTF</td>
<td>6</td>
<td>59.5</td>
<td>2.35</td>
</tr>
<tr>
<td>OBZ 6-6-1-8</td>
<td>MFPTB18N</td>
<td>3MO-3TTF</td>
<td>4</td>
<td>59.7</td>
<td>2.35</td>
</tr>
<tr>
<td>OBZ 12-12-1</td>
<td>M12FBT12M</td>
<td>5MO-3TTF</td>
<td>10</td>
<td>67.7</td>
<td>2.66</td>
</tr>
<tr>
<td>OBZ 12-12-1</td>
<td>M12FBT12M</td>
<td>12MO-3TTF</td>
<td>12</td>
<td>72.6</td>
<td>2.85</td>
</tr>
<tr>
<td>OBZ 12-12-1</td>
<td>M12FBT12M</td>
<td>12MO-5TTF</td>
<td>12</td>
<td>72.6</td>
<td>2.85</td>
</tr>
<tr>
<td>OBZ 12-12-1</td>
<td>M12FBT12M</td>
<td>10MO-5TTF</td>
<td>16</td>
<td>77.8</td>
<td>3.03</td>
</tr>
</tbody>
</table>

**NOTE:** A and C dimensions are typical finger-tight. Dimensions for reference only, subject to change.
# Tube to Tube Unions

## DEBTA, DELTA
### Dielectric Union Adapter
*For fractional tube*
Includes nuts, machined tube with molded ferrule, product ferrule, and dielectric identification ring.

<table>
<thead>
<tr>
<th>COMPRESSION PART NO.</th>
<th>4-LIN. ADAPTER PART NO.</th>
<th>TUBE END</th>
<th>TUBE END</th>
<th>L</th>
<th>E 8</th>
<th>W 8</th>
<th>V 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-8 DEBTA-45</td>
<td>9-8 DELTA</td>
<td>3/8</td>
<td>1/2</td>
<td>2.08</td>
<td>.30</td>
<td>11/16</td>
<td>.75</td>
</tr>
<tr>
<td>9-10 DEBTA-45</td>
<td>9-10 DELTA</td>
<td>1/2</td>
<td>5/8</td>
<td>2.56</td>
<td>.36</td>
<td>7/8</td>
<td>1</td>
</tr>
</tbody>
</table>

**NOTE:** Make-up instructions included with parts in box when ordered as an Adapter only. *Other and connectors available upon request.* Dimensions for reference only, subject to change.

## DEBTA, DELTA
### Dielectric Assembly
*For fractional tube*
Includes dielectric union adapter with assembled tube fitting unions

## EBZ, EE
### Union Elbow
*For fractional tube*

<table>
<thead>
<tr>
<th>COMPRESSION PART NO.</th>
<th>4-LIN. PART NO.</th>
<th>OD</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1 EBZ</td>
<td>1EE1</td>
<td>1/16</td>
<td>.76</td>
</tr>
<tr>
<td>2-2 EBZ</td>
<td>2EE2</td>
<td>1/2</td>
<td>.86</td>
</tr>
<tr>
<td>3-3 EBZ</td>
<td>3EE3</td>
<td>9/16</td>
<td>1.06</td>
</tr>
<tr>
<td>4-4 EBZ</td>
<td>4EE4</td>
<td>1/4</td>
<td>1.13</td>
</tr>
<tr>
<td>5-5 EBZ</td>
<td>5EE5</td>
<td>5/16</td>
<td>1.25</td>
</tr>
<tr>
<td>6-6 EBZ</td>
<td>6EE6</td>
<td>9/32</td>
<td>1.36</td>
</tr>
<tr>
<td>8-8 EBZ</td>
<td>8EE8</td>
<td>1/2</td>
<td>1.44</td>
</tr>
<tr>
<td>10-10 EBZ</td>
<td>10EE10</td>
<td>3/8</td>
<td>1.51</td>
</tr>
<tr>
<td>12-12 EBZ</td>
<td>12EE12</td>
<td>5/8</td>
<td>1.58</td>
</tr>
<tr>
<td>14-14 EBZ</td>
<td>14EE14</td>
<td>9/32</td>
<td>1.65</td>
</tr>
<tr>
<td>16-16 EBZ</td>
<td>16EE16</td>
<td>7/16</td>
<td>1.71</td>
</tr>
<tr>
<td>20-20 EBZ</td>
<td>20EE20</td>
<td>1</td>
<td>1.85</td>
</tr>
<tr>
<td>24-24 EBZ</td>
<td>24EE24</td>
<td>1-1/8</td>
<td>2.00</td>
</tr>
<tr>
<td>32-32 EBZ</td>
<td>32EE32</td>
<td>2</td>
<td>2.25</td>
</tr>
</tbody>
</table>

**NOTE:** **C** dimension is typical fingernail. Dimensions for reference only, subject to change.

**NOTE:** Sizes 20, 24, 32 require additional lubrication prior to assembly.

---

Parker-Hannifin Tube Union Tees

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### Tube to Tube Unions

**JBZ. ET**

**Union Tee**

*For fractional tube*

**Dimensions**

<table>
<thead>
<tr>
<th>PART NO.</th>
<th>A-LG. PART NO.</th>
<th>INTER. CONNECTIONS WITH</th>
<th>TUBE O.D.</th>
<th>A</th>
<th>C</th>
<th>L</th>
<th>H (IN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1-1 JBZ</td>
<td>1ET1</td>
<td>100-5</td>
<td>1/16</td>
<td>1.45</td>
<td>.71</td>
<td>.56</td>
<td>5/8</td>
</tr>
<tr>
<td>2-2-2 JBZ</td>
<td>2ET2</td>
<td>200-5</td>
<td>1/8</td>
<td>1.76</td>
<td>.86</td>
<td>.62</td>
<td>5/8</td>
</tr>
<tr>
<td>3-3-3 JBZ</td>
<td>3ET3</td>
<td>300-5</td>
<td>1/4</td>
<td>2.12</td>
<td>1.06</td>
<td>.77</td>
<td>1-3/16</td>
</tr>
<tr>
<td>4-4-4 JBZ</td>
<td>4ET4</td>
<td>400-5</td>
<td>1/2</td>
<td>2.44</td>
<td>1.17</td>
<td>.86</td>
<td>3/4</td>
</tr>
<tr>
<td>5-5-5 JBZ</td>
<td>5ET5</td>
<td>500-5</td>
<td>5/8</td>
<td>2.94</td>
<td>1.47</td>
<td>1-1/4</td>
<td></td>
</tr>
<tr>
<td>6-6-6 JBZ</td>
<td>6ET6</td>
<td>600-5</td>
<td>3/4</td>
<td>3.46</td>
<td>1.76</td>
<td>1-1/2</td>
<td></td>
</tr>
<tr>
<td>8-8-8 JBZ</td>
<td>8ET8</td>
<td>800-5</td>
<td>1</td>
<td>4.00</td>
<td>2.02</td>
<td>1-1/4</td>
<td></td>
</tr>
<tr>
<td>10-10-10 JBZ</td>
<td>10ET10</td>
<td>1000-5</td>
<td>1-1/4</td>
<td>4.53</td>
<td>2.25</td>
<td>1-1/2</td>
<td></td>
</tr>
<tr>
<td>12-12-12 JBZ</td>
<td>12ET12</td>
<td>1200-9</td>
<td>1-1/2</td>
<td>5.14</td>
<td>2.57</td>
<td>1-1/2</td>
<td></td>
</tr>
<tr>
<td>14-14-14 JBZ</td>
<td>14ET14</td>
<td>1400-9</td>
<td>1-5/8</td>
<td>5.76</td>
<td>2.89</td>
<td>1-1/2</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** A and C dimensions are typicallinger. Dimensions for reference only, subject to change.

**JBZ. ETM**

**Union Tee**

*For metric tube*

**Dimensions**

<table>
<thead>
<tr>
<th>PART NO.</th>
<th>A-LG. PART NO.</th>
<th>INTER. CONNECTIONS WITH</th>
<th>TUBE O.D.</th>
<th>A</th>
<th>C</th>
<th>L</th>
<th>W (IN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JBZ 2-0-2 ETM0</td>
<td>2MC-5</td>
<td>2</td>
<td>44.7</td>
<td>23.2</td>
<td>15.7</td>
<td>3/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 3-0-3 ETM0</td>
<td>3MC-5</td>
<td>3</td>
<td>44.7</td>
<td>23.2</td>
<td>15.7</td>
<td>3/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 4-0-4 ETM0</td>
<td>4MC-5</td>
<td>4</td>
<td>50.8</td>
<td>25.4</td>
<td>16.6</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>JBZ 6-0-6 ETM0</td>
<td>6MC-5</td>
<td>6</td>
<td>69.7</td>
<td>32.9</td>
<td>22.4</td>
<td>5/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 8-0-8 ETM0</td>
<td>8MC-5</td>
<td>8</td>
<td>93.5</td>
<td>44.6</td>
<td>30.3</td>
<td>7/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 10-0-10 ETM10</td>
<td>10MC-5</td>
<td>10</td>
<td>109.2</td>
<td>55.1</td>
<td>40.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>JBZ 12-0-12 ETM12</td>
<td>12MC-5</td>
<td>12</td>
<td>124.9</td>
<td>60.1</td>
<td>46.3</td>
<td>1-1/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 14-0-14 ETM14</td>
<td>14MC-5</td>
<td>14</td>
<td>140.8</td>
<td>66.8</td>
<td>53.4</td>
<td>1-1/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 15-0-15 ETM15</td>
<td>15MC-5</td>
<td>15</td>
<td>156.7</td>
<td>72.2</td>
<td>60.6</td>
<td>1-1/8</td>
<td></td>
</tr>
<tr>
<td>JBZ 16-0-16 ETM16</td>
<td>16MC-5</td>
<td>16</td>
<td>172.5</td>
<td>78.2</td>
<td>67.9</td>
<td>1-1/8</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** A and C dimensions are typical linger. Dimensions for reference only, subject to change.
ZHBA, MISC
Male Connector to SAE Straight Thread
For fractional tube

Color Coding
For easy reference, bold heads are color indicated as follows:

fractional

metric

Parker-Hannifin Straight Thread Plug
The highlighted item represents the pressure rating used by Parker engineers for straight thread fittings.

Parker-Hannifin A-Lok Female Pipe Adapter
**Tube to Female Pipe**

**GBZ, FSCN**

**NPT Female Connector**

*For fractional tube*

**GBZ, FSCN**

**NPT Female Connector**

*For metric tube*

### Table: Inter-Changes with A-Lock Part No.

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Inter-Changes With</th>
<th>Tube O.D.</th>
<th>NPT Pipe Thread</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>W</th>
<th>Hex</th>
</tr>
</thead>
</table>

- GBZ 1-1 GBZ 1FSC1N 500-7-1 1/16 1/16 .93 .43 .78 .78 1-16
- GBZ 2-1 GBZ 1FSC2N 500-7-2 1/16 1/16 .95 .43 .61 .51 1-16
- GBZ 3-1 GBZ 1FSC3N 500-7-3 1/16 1/16 1.14 .66 .68 .68 1-16
- GBZ 4-1 GBZ 1FSC4N 500-7-4 1/16 1/16 1.32 .90 .90 .90 1-16
- GBZ 5-1 GBZ 1FSC5N 500-7-5 1/16 1/16 1.17 .64 .64 .64 1-16

### Table: Inter-Changes with A-Lock Part No. (Metric)

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Inter-Changes With</th>
<th>Tube O.D.</th>
<th>NPT Pipe Thread</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>W</th>
<th>Hex</th>
</tr>
</thead>
</table>

- GBZ 3-1 GBZ 1FSC1N 200-7-1 1/16 1/16 1.95 .64 .90 .90 1-16
- GBZ 4-1 GBZ 1FSC2N 400-7-2 1/16 1/16 2.13 .70 .64 .66 1-16
- GBZ 5-1 GBZ 1FSC3N 400-7-3 1/16 1/16 2.42 .70 .64 .64 1-16
- GBZ 6-1 GBZ 1FSC4N 400-7-4 1/16 1/16 2.40 .70 .64 .64 1-16
- GBZ 7-1 GBZ 1FSC5N 400-7-5 1/16 1/16 2.17 .70 .64 .64 1-16

---

**NOTE:** A and C dimensions are typical finger-tight. Dimensions for reference only. Subject to change. 

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**Fuji Electric Panel Meter**

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Panel meter produced by Fuji Electric; compatible with transducer given on following page

FD5000

ONE UNIVERSAL PANEL METER FOR A VARIETY OF INPUT NEEDS

Fuji Electric's new FD5000 is a highly modular 1/8 DIN panel meter with up to 19 different field-replaceable input boards. No need to stock a variety of panel meters — simply install the appropriate input board for each process.

The FD5000 offers optional alarms and analog outputs, in addition to RS232 or RS485 communications functions. Easily connect the FD5000 to a PC to process and control various data.

The FD5000 accepts inputs from temperature probes, pressure transducers, load cells, strain gauges, potentiometers, pulse inputs, large voltage and current signals. This makes it ideal for demanding process applications such as Food, Textiles, and Automotive.

FEATURES

• Free Power Supply Voltage
  90 to 264VAC, 9 to 60VDC

• RS-232 or RS-485 Function
  For serial communication with a computer

• Loop Power Option
  1 to 5V, 4 to 20mA input with 12.24V excitation voltage

• Digital Zero Function
  Zeros indication at any time

• Hold Feature
  Temporarily retains the indication

• Peak Hold Function
  Retains maximum or minimum value and provides corresponding output

• Comparison Output Function
  Relay output based on HI and LO setpoints

• Analog Output Function
  Scalable DC voltage or current output

MODULAR FIELD-REPLACEABLE BOARDS

Main Board — 2 Types
90 to 264VAC power supply, or
9 to 60VDC power supply

Display Board — 2 Types
  Single display, or
  Multiple (HI and LO setpoint) display

Output Board — 7 Types
  HI&LO setpoint,
  Analog output,
  RS-232,
  RS-485,
  HI&LO setpoint + analog output,
  HI&LO setpoint + analog output + RS-232, or
  HI&LO setpoint + analog output + RS-485

Input Board — 19 Types
  DC voltage (±99.99mV),
  DC voltage (±999.9mV to ±600V),
  DC current (±9.999mA to ±99.99mA),
  AC voltage AVG (±99.99mV to ±9.999V),
  AC voltage AVG (±99.99V to ±600V),
  AC voltage RMS (±99.99mV to ±9.999V),
  AC voltage RMS (±99.99V to ±600V),
  AC current AVG (±9.999mA to ±99.99mA),
  AC current AVG (±5A),
  AC current RMS (±9.999mA to ±99.99mA),
  AC current RMS (±5A),
  Resistance (99.99Ω to ±999.9Ω),
  Temperature (Thermocouple),
  Temperature (RTD),
  Frequency (Open collector, Logic, Magnet),
  Frequency (50 to 500Vrms),
  Strain gauge,
  1 to 5V, 4 to 20mA, or
  1 to 5V, 4 to 20mA, with 12.24V Excitation Voltage
Analog pressure transducer produced by AST

AST4400  Class 1 Div 1 IS Groups C, D with Approved Barrier
Stainless Steel Media Isolated Pressure Sensor

OVERVIEW
The AST4400 is a media isolated stainless steel pressure sensor with a wide variety of options. In addition to its rugged construction and best price-to-performance ratio in the industry, the AST4400 is the solution for pressure measurement in Intrinsically Safe areas.

BENEFITS
- High Strength Stainless Steel Construction
- No Oil, Welds or Internal O-rings
- Wide Operating Temperature Range
- Ranges up to 10,000 PSI
- Low Static and Thermal Errors
- Unparalleled Price and Performance
- Compatible with Wide Range of Liquids and Gases
- EMI/RFI Protection
- UL/cUL 913 Class 1 Div 1 Groups C,D when installed with an approved barrier

APPLICATIONS
- Industrial OEM Equipment
- HVAC/R Equipment
- Water Management
- Control Panels
- Pneumatics
- Hydraulic Systems
- Hydrogen Storage (316L SS)
- Control Panels
- Hydraulic Systems
- Data Loggers

Performance @25°C (77°F)
- Accuracy* < ±0.25% BFSL
- Repeatability ±0.125% FS typ
- Over range Protection 2x Rated Pressure
- Burst Pressure 5X or 10,900 psi (whichever is less)
- Pressure Cycles > 100 Million

Environmental Data
- Temperature
  - Operating -40 to 85°C (-40 to 185°F)
  - Storage -40 to 100°C (-40 to 212°F)
- Thermal Limits
  - Compensated Range 0 to 55°C (32 to 131°F)
  - TC Zero < ±1% of FS
  - TC Span < ±1% of FS
- Other
  - Shock 1000, 11 msec, 1/2 sine
  - Vibration 10G peak, 20 to 2000 Hz
  - EMI/RFI Protection: Yes
  - Rating: IP-65

Electrical Data
- Output 4-20mA, 1-5VDC, 1-6VDC, 0-50mV, 0.5-4.5V Ratiometric
- Excitation 10-28VDC
- Output Impedance >10k Ohms
- Current Consumption 2mA typ
- Bandwidth (3dB) DC to 250 Hz
- Output Noise -2mV RMS
- Zero Offset < ±1% of FS
- Span Tolerance < ±2% of FS
- Output Load >800 Ohms
- Reverse Polarity Protection Yes

TTI Instruments
www.ttitglobal.com • 1-800-235-8307
8 Leroy Road, PO Box 1073 Williston, VT 05495
Phone: (802) 863-0085 Fax: (802) 863-1193
Email: sales@ttitglobal.com

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Peter-Paul Solenoid Valve

SERIES 20 MODEL H22 & EH22
2-WAY NORMALLY CLOSED HIGH PRESSURE IMPACT TYPE SOLENOID VALVE

EXCLUSIVE FEATURES INCLUDE:
- A precision stainless steel PLUNGER that supplies the necessary impact force to energize valve.
- A Kel-F PIN which functions as a seating element, that is carefully machined for maximum concentricity and fine finish.
- The ORIFICE GUIDE is one piece, for near perfect alignment. This means bubble-tight sealing from low pressures right up to maximum pressure rating with the bonus of longer life. The one piece Orifice/Guide can be pressed into almost any standard cavity making it available as an operator for special customer installations.
- Other pin materials available, consult factory PATENTED

OTHER FEATURES INCLUDE:
- Simple construction...
- Only 2 moving parts
- Available in both standard and explosion proof construction
- 1/4 or 1/8 NPT ports

PRINCIPLES OF OPERATION
When the valve coil is energized, the plunger is drawn towards the sleeve end stop. The plunger is allowed to accelerate freely for a short distance before it makes contact with the pin shoulder. Upon contact it imparts considerable force on the pin causing it to lift off the seat. A return spring provides the return force, directly on the pin, to seal the orifice when the coil is de-energized.

OPTIONS AVAILABLE: 2 WAY NORMALLY CLOSED HI-PRESSURE VALVE

- "STRAIN RELIEF CONNECTOR"
- "TANK AUTOMOTIVE"
- "TANK CONNECTION"

Note: When ordering, add voltage and frequency to complete valve number (Example H22DHCOV—120-60)
To order operator only, add 0" to part in valve number (Example 43550DA—120-00)
Solenoid Valves...

SERIES 20 MODEL H22 2-WAY NORMALLY CLOSED—HIGH PRESSURE

<table>
<thead>
<tr>
<th>GAS PRESSURE RATINGS</th>
<th>ORIFICE SIZE</th>
<th>CV FACTOR</th>
<th>GROMMET</th>
<th>VALVE NUMBER</th>
<th>EXPLOSION PROOF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/8 NPT</td>
<td>1/4 NPT</td>
<td>1/2 NPT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC DC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>3000</td>
<td>1.32</td>
<td>J02</td>
<td>H22G7DGV</td>
<td>H22G9DGV</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H22H7DGV</td>
<td>H22H9DGV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>H22J7DGV</td>
<td>H22J9DGV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H22K7DGV</td>
<td>H22K9DGV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIQUID PRESSURE RATINGS</th>
<th>ORIFICE SIZE</th>
<th>CV FACTOR</th>
<th>GROMMET</th>
<th>VALVE NUMBER</th>
<th>EXPLOSION PROOF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/8 NPT</td>
<td>1/4 NPT</td>
<td>1/2 NPT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC DC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>3000</td>
<td>1.32</td>
<td>J02</td>
<td>H22G7DGV</td>
<td>H22G9DGV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H22H7DGV</td>
<td>H22H9DGV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H22J7DGV</td>
<td>H22J9DGV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H22K7DGV</td>
<td>H22K9DGV</td>
</tr>
</tbody>
</table>

SPECIFICATIONS

SERIES 20—MODEL H22

Three-way normally closed valve for high pressure applications. Valve must be mounted within 30° of vertical.

OPERATING CONDITIONS

- Media: Air and other non-corrosive gases, water and oil.
- Valve Temperature Range: Standard Valve-0°F (-18°C) to 150°F (65°C) ambient. Optional Valve can tolerate much higher or much lower ambient and media temperatures. Consult factory for specifics.
- Burst Pressure: 5000 PSI
- Maximum Operating Pressure Differential: to 3000 PSI

ELECTRICAL CHARACTERISTICS

- Coil Voltage: 5 to 825 VAC, 50-60 Hz. 5.8 to 265 VDC
- Nominal Power: H22 22 watts
  - A.C. 7.7 watts
  - D.C. 9.5 watts
- Coil Construction: Standard Valve—molded coil and third wire ground (standard)
  - Explosion Proof Valve—molded coil and explosion proof third wire (standard)
- Typical Response Time on Air: 4-16 milliseconds

MECHANICAL CHARACTERISTICS

- Body: Stainless Steel
- Orifice Diameter: 1/8” to 3/4” NPT
- Housing: Standard Valve—1/2” NPT conduit and grommet
  - Explosion Proof Valve—1/2” NPT conduit and grommet with third wire ground (EP only)

STANDARD

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>EXPLOSION PROOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROMMET HOUSING</td>
<td>WT. 1.04 LB.</td>
</tr>
<tr>
<td>CONDUIT HOUSING</td>
<td>WT. 1.15 LB.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AIR FLOW (SCFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

P - INLET PRESSURE (PSI)  P - 0

<table>
<thead>
<tr>
<th>PRESSURE DROP (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

0.5¢ = 85

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Clark Cooper Solenoid Valve

**EH 50 SERIES**

**1/2" PIPE SIZE • FULL PORT**

**OPERATION:**
The normally closed valve opens when energized and closes when de-energized. When the coil is energized the pilot valve opens, relieving the pressure above the piston, which is then lifted from its seat by the inlet pressure. Upon de-energizing the coil, a spring closes the pilot valve and pressure builds above the piston to seat it. The normally open valve operates similarly, closing when energized and opening when de-energized.

**APPLICATION:**
To control the flow of High Pressure Air, Water, Natural Gas, Hydrogen, Nitrogen and other gases or light liquids compatible with materials of construction. Valve must be mounted with solenoid vertical and on top.

**CONSTRUCTION**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve Body</td>
<td>7075-T6 Aluminum, Anodized</td>
</tr>
<tr>
<td>Piston</td>
<td>PEEK®</td>
</tr>
<tr>
<td>O Rings</td>
<td>Buna-N</td>
</tr>
<tr>
<td>Backing Rings</td>
<td>Buna-N</td>
</tr>
<tr>
<td>Piston Ring/Seal</td>
<td>Teflon®, Silicone</td>
</tr>
<tr>
<td>Cartridge</td>
<td>316 SS/430 SS</td>
</tr>
<tr>
<td>Pilots/Seal</td>
<td>303 SS/Teflon®</td>
</tr>
<tr>
<td>Spring</td>
<td>302 SS</td>
</tr>
<tr>
<td>Plunger</td>
<td>430 SS</td>
</tr>
<tr>
<td>Bonnet Retainer</td>
<td>430 SS</td>
</tr>
<tr>
<td>Cartridge Gasket</td>
<td>Nylon</td>
</tr>
<tr>
<td>Fluid Temperature Range:</td>
<td></td>
</tr>
<tr>
<td>Buna:</td>
<td>-50°F to 230°F</td>
</tr>
<tr>
<td>Viton:</td>
<td>-10°F to 400°F</td>
</tr>
<tr>
<td>Shipping Weight:</td>
<td>5 LBS. (C_{v}=4.5)</td>
</tr>
</tbody>
</table>

**ELECTRICAL**

<table>
<thead>
<tr>
<th>Model: EH50-08-XXXX-XX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power:</td>
</tr>
<tr>
<td>(STD) 10 Watts</td>
</tr>
<tr>
<td>AC Inrush:</td>
</tr>
<tr>
<td>AC Holding:</td>
</tr>
<tr>
<td>Insulation:</td>
</tr>
<tr>
<td>Duty:</td>
</tr>
<tr>
<td>Enclosure:</td>
</tr>
<tr>
<td>Connection:</td>
</tr>
</tbody>
</table>

**Pressures**

<table>
<thead>
<tr>
<th>Model: EH50-08-XXXX-XX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Operating Pressure:</td>
</tr>
<tr>
<td>AC Voltage (STD): 7,500 PSIG</td>
</tr>
<tr>
<td>AC Voltage (XP): 10,000 PSIG</td>
</tr>
<tr>
<td>DC Voltage (STD): 5,000 PSIG</td>
</tr>
<tr>
<td>DC Voltage (XP): 5,000 PSIG</td>
</tr>
<tr>
<td>Minimum Pressure:</td>
</tr>
</tbody>
</table>

**Options**

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>Integrated Check Valve</td>
</tr>
<tr>
<td>SS</td>
<td>316 SS Valve Body</td>
</tr>
<tr>
<td>HY</td>
<td>Hydrogen Service</td>
</tr>
<tr>
<td>NO</td>
<td>Normally Open, Energize to Close</td>
</tr>
<tr>
<td>VT</td>
<td>Viton Seal</td>
</tr>
<tr>
<td>OX</td>
<td>Oxygen Clean</td>
</tr>
<tr>
<td>XP</td>
<td>Pressures up to 10,000 PSIG - (AC Voltage)</td>
</tr>
<tr>
<td></td>
<td>Pressures up to 5,000 PSIG - (DC Voltage)</td>
</tr>
<tr>
<td></td>
<td>(Only available with AC Voltages)</td>
</tr>
</tbody>
</table>

Clark Cooper Div.
Magnatrol Valve Corporation
855 Industrial Highway, Unit 4, Cinnaminson, NJ 08077

Tel: (856) 829-4580 • Fax: (856) 829-7303
techsupport@clarkcooper.com www.clarkcooper.com

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HydroKnowz Hydrogen Sensor

HydroKnowz™

Catalytic Hydrogen Gas Monitor

FEATURES
- Catalytic Sensor & HCMOS microcontroller
- 0–25,000 ppm hydrogen in air measurement
- 100 ppm logical resolution (120 ppm: 4–20mA)
- 2 seconds start-up time
- 2 secs. T90 response time
- 5 secs. T10 recovery time
- Normal, Warning, Alarm & Error states
- B-color LED status indicator
- Optional NO or NC dry relay
- Manual reset or auto-resetting operation
- Optional 0-to-3V proportional output (8 bit)
- Optional 4-20mA proportional output (8 bit)
- Optional binary operation (TTL output)
- Optional alarm beeper
- PK-Port™ compatible digital communications
- User-settable alarm/warning via PK-Port™
- Digital FLASH-based calibration
- Each device factory pre-calibrated
- Field re-programmable firmware
- -40 to +80 Celsius operation
- Sensor & temperature error detection
- 100mW power consumption
- Optional 3VDC input power version (11)
- Optional 5-40VDC input power version (12)
- Optional 5-60VDC input power version (13)
- 61mm x 48mm x 26mm circuit-only size

DESCRIPTION
The Neodym HydroKnowz™ is an intelligent hydrogen gas monitor intended for safety applications in power generation equipment. The sensor has a VOC filter, cannot be damaged by overexposure and has increased tolerance of silicone-based contaminants. Linear measurement of hydrogen (in air) concentrations is possible up to 25,000 ppm with about 100 ppm resolution. Each device is factory calibrated to a user-specified alarm point. Calibration values are FLASH memory-based and are field-adjustable via Neodym’s PK-Port™ PC interface. The device operates at 3VDC and consumes about 1000mW. Wide input supply versions are available. Custom form factors, connector types and mounting provisions are available by special order.

BLOCK DIAGRAM

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Matlab Code

Used to Generate Figure 27 through Figure 29

1 clear; clc
2 format short e
3
4 RPM = [600 800 1050 1300 1550 1800 2200 2600 3100 3600 4100 4600];
5
6 VI = [0.92 0.75 0.6 0.5 0.4 0.3 0.2 0.1 0.0499];
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8 AFCNG = 17.2;
9 AFH2 = 34;
10
11 Hair = 28.97;
12 MH2 = 2.02;
13
14 ARatio = [0 0.00310559 0.00621118 0.077639752 0.161490683 0.301242236 0.434782609 0.574534161 0.692546504 0.7901036646 0.87577698 0.9316770019 0.978206087 1 0.90136646 0.947204969 0.87577659 0.795031055 0.680124224 0.559006211 0.422360248 0.263975155 0.07424161 0.00931677 0.00421110 0.00621110
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BIBLIOGRAPHY


VITA
Graduate College
University of Nevada, Las Vegas

Julian J. L. Gardner

Local Address:
8057 Retriever Ave
Las Vegas, Nevada 89147

Home Address:
908 East Oakey Blvd
Las Vegas, Nevada 89104-2802

Degrees:
Bachelor of Science, Mechanical Engineering, 2005
University of Nevada, Las Vegas

Special Honors or Awards:
Outstanding Graduate, Mechanical Engineering, December 2005

Publications:


Thesis Title: Conversion and Performance Evaluation of a Hydrogen Powered Ford F250 Pickup Truck.

Thesis Examination Committee:
Chairperson, Dr. Robert Boehm, Ph. D.
Committee Member, Dr. Brendan O’Toole, Ph. D.
Committee Member, Dr. Woosoon Yim, Ph D.
Graduate Faculty Member, Dr. Yahia Baghzouz, Ph. D.