Hydrogen Component Performance Diagnostic Testing

Cooperative Research and Development Final Report

CRADA Number: CRD-18-743

NREL Technical Contact: Daniel Leighton

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-76891
June 2020

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Cooperative Research and Development Final Report

Report Date: April 27, 2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: RIX Industries

CRADA Number: CRD-18-743

CRADA Title: Hydrogen Component Performance Diagnostic Testing

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$57,000.00
TOTALS	$57,000.00

Abstract of CRADA Work:

H2@Scale is focused on the wide scale adoption of hydrogen as a flexible energy storage medium. Due to the low volumetric energy density of gaseous hydrogen, compressors are an essential component of hydrogen storage. Hydrogen compressors that support a flexible grid and on-demand vehicle fueling undergo challenging operating conditions, such as a high number of start and stop cycles and wide input and discharge pressure ranges. Equally robust components are required for these conditions while still meeting the financial requirements of sustainable hydrogen compression.

Summary of Research Results:

Task 1: Design Test Apparatus and Protocol AND Task 2: Valve Testing

Summary:
The following sections are a report provided to RIX Industries at the conclusion of the project detailing the work done on Tasks 1 and 2, and where they can continue development if they chose. NREL completed Task 1 as detailed in the report below via delivery of a design of a test apparatus and protocol. Task 2 was incomplete, as a fully functional prototype test device was not built or delivered due to numerous technical challenges due to the novel nature of the technology that lead to higher than expected labor costs. In concert with RIX Industries, we decided to cease further development on Task 2 part-way through in order to focus the remaining labor budget on the compressor testing task (Task 3), which was deemed of greater importance.

I (Daniel Leighton) was not the original PI of the project at the start date, only toward the end was it changed to me. However, I was the lead engineer during the entire duration of the testing, and I wrote all of this report.

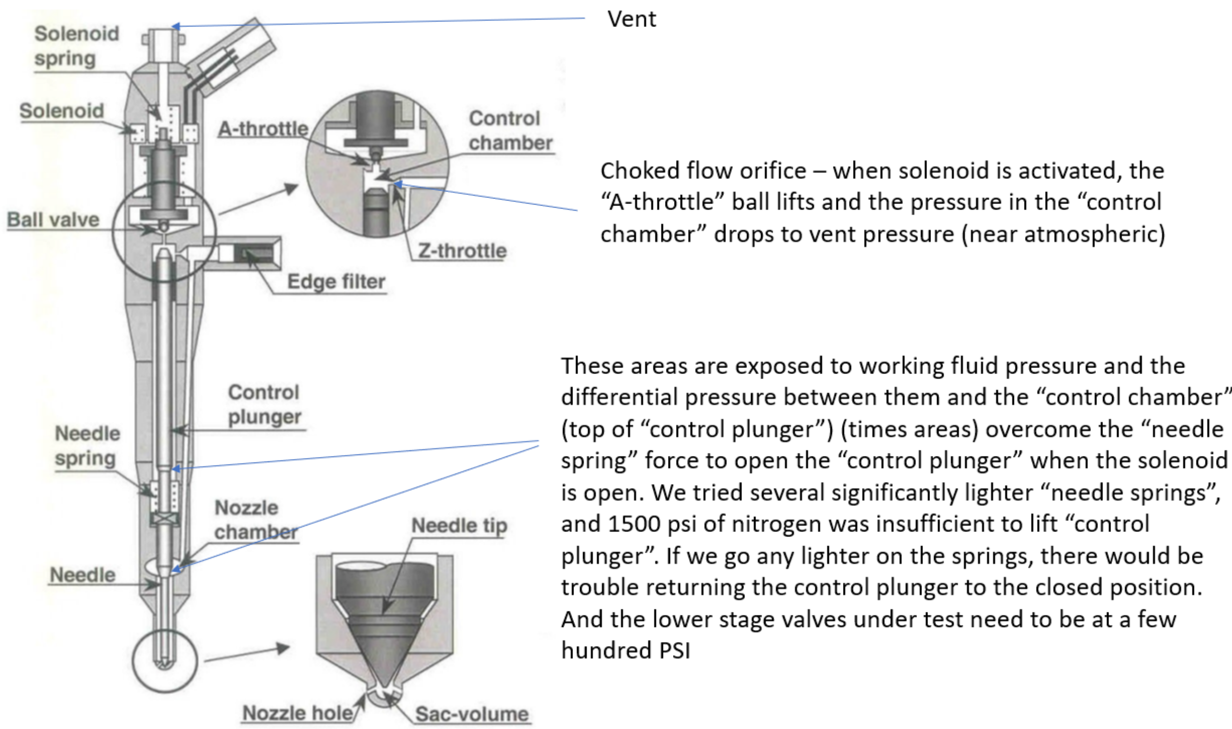
Introduction:

This report is a summary of the NREL work to develop a high cycle (long life), high-speed test apparatus for RIX compressor reed valves from off-the-shelf stationary power/vehicle engine fuel injectors (for diesel, natural gas, or gasoline engines). The report makes note of the lessons learned and the intended next steps if the work were to be continued by RIX. It also explains the files (drawings, etc.) provided. A fuel injector approach was chosen because of the extreme cycle life (>10^8 cycles), high speed control (order of milliseconds), cheap parts available off-the-shelf/ease of replacement, and theoretical ease of "tuning" of the pressure cycle "profile" via small changes in the programming/timing of the fuel injector actuation. Additionally, the adjustment of the up and downstream pressures via hand regulators will allow precise tuning of the mass flow rate through the fixed orifice size.

Selection of fuel injectors:

Many types of fuel injectors were considered including diesel, gasoline, compressed natural gas, as well as many different technology designs (direct acting, pressure assisted, pressure driven, etc.). We looked across multiple industries for different sized engines including high performance vehicles, regular light-duty vehicles, large consumer trucks, class 8 trucks, stationary power units, ships, trains, etc. The biggest challenge in selecting a fuel injector was found to be the selection of a fuel injector with sufficiently large orifice size (flow coefficient), sufficiently large pressure rating, and one capable of actuating at a wide range of pressures (high turn-down). It was found that natural gas injectors had large orifices, but insufficient pressure ratings. Typical gasoline engine injectors had low/mid-pressure ratings and mid-range orifices, but the pressure ratings were insufficient for the higher compression stages of the RIX compressor. Modern diesel injectors had extremely high-pressure ratings (much higher than required for the RIX compressor testing) but had relatively smaller orifice sizes, at least for light duty vehicles. Larger/heavy duty diesel engines typically had larger orifice sizes but didn't have high enough pressure ratings because they are run on older, lower pressure diesel injection technology. The high-pressure diesel injectors are used in light-duty vehicles to provide better combustion and reduced emissions (to meet regulatory requirements).

We selected a modern diesel injector to bench test from a consumer light-duty truck (Engine: LBZ 2006-2007 Chevrolet/GMC 2500/3500/4500/5500 6.6 L diesel; Injector: Bosch Part #0445120042; Source: https://www.injectorsdirect.com/product/lbz-bosch-oem-new-fuel-injectors/). One of the biggest issues with the modern diesel injectors is that they use the electromagnetic coil to actuate a secondary system that allows fluid pressure to open the main pintle ("control plunger" in the drawing below) by overcoming a balancing spring force via an extremely small "shoulder" area on the pintle (see image below, which is nearly identical in function to the Bosch diesel injector). This means that they don't have much "turn-down" capability and require extremely high (~200 MPa) pressures to fully actuate properly (in a diesel engine a high-pressure pump supplies this pressure on a constant basis). We tried a variety of springs (with different spring constants), but even extremely light spring constants were not sufficient to allow actuation at low pressures (<1,500 psig). The other issue is that too low of a spring constant would be insufficient to allow re-seating/re-sealing of the pintle to block flow, as the injector is designed for much higher pressures.



The type of injector found to be most promising is one of the most recently developed pieces of technology which is the high-pressure gasoline injector. One of the main reasons that they were selected for testing is that they work through direct electro-magnetic coil actuation (the electrical coil directly lifts the main pintle that allows fluid injection). This means that it has an infinite turndown (can open with zero upstream pressure) – which is very advantageous to the system design. We found an injector with at least a 200-bar pressure rating, which is sufficient for the application.

These modern high-pressure gasoline injectors are a new technology that is not yet widespread and are very limited in supply (only Bosch so far from what we've seen). They have been used in a few mass-produced consumer high performance light-duty vehicles (BMW, etc.). It is also possible to get custom units designed, but the price was prohibitive at low volume, so instead an off-the-shelf unit was selected that has sufficient pressure rating (200 bar).

One item of note is that although it appears the body and tubing (wetted parts) of both the diesel and high-pressure gasoline fuel injectors are primarily stainless steel, we did not conduct testing (or contact the manufacturer) to confirm the materials of construction. We wanted to prove initial feasibility of the approach using nitrogen before moving to hydrogen testing. If hydrogen testing were to be conducted, material compatibility would need to be ensured.

Bench testing of fuel injectors:

The diesel injector that we tested can be disassembled (and rebuilt). The injector was left in a disassembled state the last time we tested it (after determining that no further testing or use was required as it didn't meet our requirements). We also believe the actuation coil on it was damaged due to overheating during later testing (after flow data was collected). We actuated the coil with 12 VDC and it drew >20 A. It is shown in the image below with an adapter fitting from an auto parts store that was designed for one of the vehicle engines that uses this injector. The adapter ultimately goes to a 3/8” Swagelok tube fitting.

There are two identical high-pressure gasoline injectors. One of the injectors is still fully functional. The only modification from a stock unit on the functional injector is that the tip is ground down to allow higher flow rate through a single opening rather than the pattern of six ports, but the “ball” seal at the end of the pintle still seats properly – this was done after initial testing in the stock configuration. We used a precision surface grinder to remove some of the tip of the injector (and end of the ball seal) so that there was one large tip exit (see image below). This was a relatively easy modification to make and provided a nearly 40% increase in flow. Since the injectors are cheap and easy to replace if one is damaged it is likely worth repeating this modification for additional units to attain higher flow coefficients so that less units are needed in parallel to provide the desired flow rates.

The second injector has been purposely destructively disassembled and no longer will close to seal pressure (though the coil still works, so it can be used to test power supply actuation, etc.). As mentioned, we attempted to remove the tip of a second, spare injector to see if it was possible (see image below). It wasn't clear if it was welded or not. Results show that it was sintered and welded (so it is impossible to disassemble the unit in any way without damage). The deconstruction was done prior to grinding the first unit in order to give us insight into the seal design.

The bench top testing simply used a bench top 12 VDC power supply with the connection made and unmade manually by hand (rapid connection by simply touching a probe to complete the circuit). A laboratory bottle of nitrogen was used with a regulator and gauge set to provide and measure pressure up to 1,500 psig. A Micro Motion Coriolis mass flow meter (extra one in the laboratory borrowed temporarily for this test) was used for high accuracy mass flow measurement for the diesel injector. The mass flow meter was unavailable for the later high-pressure gasoline injector testing, and so instead a high-accuracy laminar flow element with differential pressure transducer was used to measure the volumetric flow rate (also extra equipment in the laboratory borrowed temporarily for this test). The tip of the injector simply exhausted to ambient atmosphere so that we could back-calculate the flow coefficient using choked flow equations, known mass flow rate, and known inlet pressure. We would open the valve via electromagnetic coil actuation for <2s at a time and take snap shots of data from that mass flow meter. These measurements are summarized for both injectors under a variety of configurations in the "Experimental Data of N2 testing of Injectors.xlsx" file.

The summary of the findings is that the diesel injector pintle would not actuate (open to allow flow) at all at 1,500 psig when the electromagnetic solenoid was opened. This is due to the lack of balancing pressure discussed previously. Also, it was found that there was a constant bleed rate of fluid through the solenoid itself (rather than through the injector tip) to provide cooling and lubrication in a diesel engine. This would be very disadvantageous in a design for the valve test apparatus as there would be a continuous loss of gas that would need to be vented. We performed tests to correct for the flow rate through the solenoid to calculate the flow through the injector tip itself (desired portion). The theoretical maximum flow limit was calculated by removing the balancing spring and running the pintle "wide open", then subtracting the flow rate from when the pintle is fully closed and the injector only flows gas through the solenoid cooling bleed-off. The maximum flow coefficient was found to be 0.017 in this ideal case. When testing different spring constants it was found that the flow would be slightly reduced from this number (presumably the pintle not opening quite as far). A test was also performed without the tip assembled, therefore without any control at all (an unrealistic, unusable configuration) and the flow coefficient was found to be 0.267 through the body itself. This verified that most of the flow restriction is through the nozzle tip, an expected result. Overall the conclusion was that the diesel injector would not actuate and reseat as needed for the testing, would constantly bleed gas (wasting capacity for testing), and the flow coefficient was rather small (which would require many parallel injectors for our needs). Therefore, it was determined that it would not work for the test apparatus we were intending to build.

These findings and research eventually led us to the direct solenoid coil activation high-pressure gasoline injector. For this unit we tested it without modification and found the flow coefficient to be 0.042 (2.5 times larger than the diesel unit). Also, because it was direct acting, it actuated well in its stock configuration regardless of feed pressure. This unit also does not have a recirculating/venting bleed port for cooling, so when it is off, there is no gas flow. For the unit that the tip was broken off from, where the ball seal was no longer functional, the flow coefficient was found to be 0.53 through the body itself. Again, this is the maximum theoretical value, but just like the diesel injector case, not a realistic or useable configuration (just confirmation that the flow restriction is mainly the nozzle tip). When we used the precision surface grinder to open the tip nozzle orifice, the flow coefficient was increased to 0.058. It may be worth grinding the tip down further to see if the flow coefficient can be increased even more without removing the ability for the ball seat to seal. Though we did grind nearly half of the ball seat off (which is the point at which it would be no longer possible to seal), so there probably isn't much room to increase the opening.

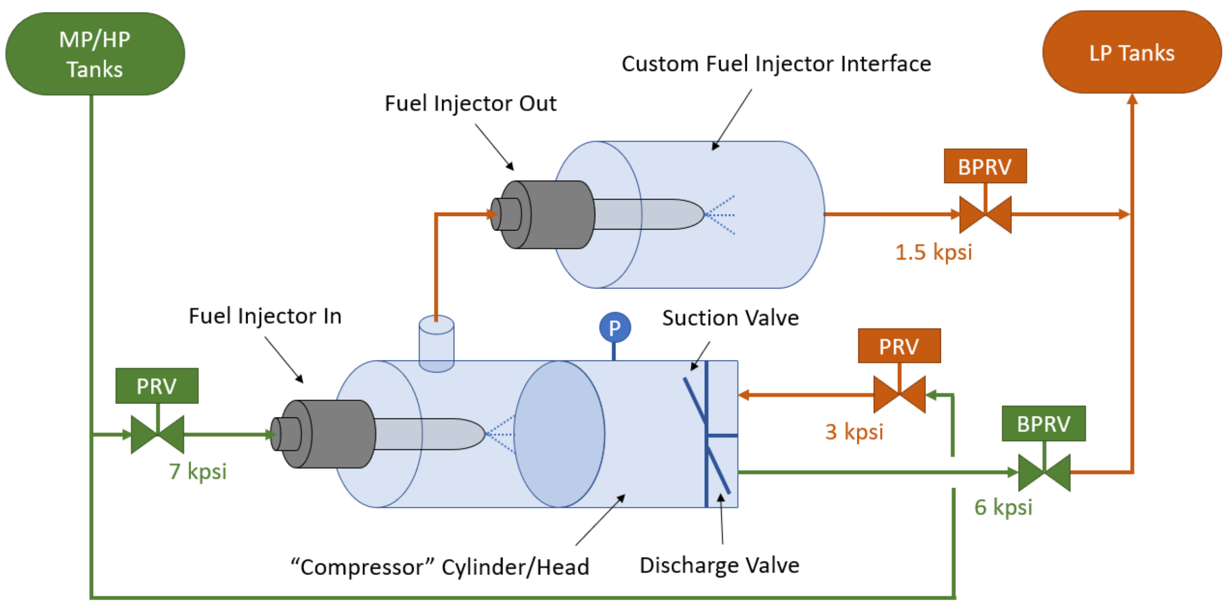
Next steps for the work (machining plans):

Now that experimental bench test measurements have estimated the flow coefficient of the high-pressure gasoline fuel injectors, and verified that the direct acting solenoid functions at any pressure turn-down, it is now time to test whether or not the injectors will be able to provide the core functionality of recreating compressor discharge and suction cycles (high-speed control). To do this, the fuel injectors must be assembled into the final system configuration so that they can interact with the actual reed valves under test and use high-speed pressure transducers to measure performance. This requires machining interfaces to seal the injectors and the compressor head into a single compressor cylinder simulator. The plan for machining was to build to parts as drawn in the CAD files. There would be one "cylinder" portion with a single fuel injector as the high-pressure inlet (drawing: injector_to_NPT_JTM_0.pdf) that is interfaced with the compressor head. The flow coefficient of the high-pressure inlet should be sufficient to provide the flow out of the discharge valve with only one injector. This "cylinder" would have three outlet ports that would lead (though extremely short adapter lines) to three outlet (low pressure side) fuel injectors that actuate in parallel with one another to provide sufficient flow capacity. You will note that the current drawing only has two outlet ports, so this would need to be updated to three outlet ports distributed around the circumference (based on experimental measurement of the flow capacity of the fuel injectors being used and the required suction valve flow rate). The 5-inch diameter stock isn't required for strength, it is just to make it easier to mate to the compressor cylinder head via the existing mounting holes. The associated 5 inch "Retainer" would also need to be machined to clamp the fuel injector into place. Three of the smaller outlet adapters to NPT fittings would also need to be machined (drawing: injector_to_NPT_JTM_0.pdf). The associated 2-inch hold-down plates for the fuel injectors would also be required to hold the fuel injectors in place. We chose NPT thread for the piping outlet for ease of assembly and part procurement, but obviously you can customize this as needed.

The plan was to use reaming bits (listed in the document: RIX_required_materials_rev_3.xlsx) to follow the drill bits for exact finish dimensions for proper fit and seal of the fuel injectors. We intended to use the existing O-rings that are provided with the fuel injectors for initial nitrogen testing (though it is possible through trial and error that it is determined that a different sealing material should be used). The exact fit dimensions based on O-ring squish was calculated based on industry norms and engineering judgement, since we didn't have the dimensions of the engine block port for the fuel injector. One issue is that we don't know what material the O-rings are made from, so for hydrogen service it would be likely that a compatible, known material would need to be selected instead. Of note, we have also carefully measured the dimensions of the fuel injector to provide a part drawing of the tip as well, for use in checking the fit of the drawing.

Since we haven't machined any of these parts yet, obviously you may need to make tweaks and changes to the design to accommodate any unforeseen realities of the machining. We planned to use 316SS, and we performed some basic FEA analysis to confirm that the design was sufficient from a pressure containment perspective. The FEA analysis is included in the files, but is incomplete, so consider the sufficiency of the design from a strength perspective before machining as well (which RIX has more expertise in than we do anyway).

Future testing (subsequent tests after machining):
After machining the interface parts and purchasing the needed additional fuel injectors, the next planned step was to connect nitrogen to the fully assembled system (including all four fuel injectors and the compressor head with reed valves). This would also require the purchase of suitable regulators to complete the design shown in the image below (although the drawing uses hydrogen source and sink tanks instead of a nitrogen source and atmosphere sink as was planned for the preliminary testing). Then a high-speed NI cDAQ digital output card could be connected to each of the four fuel injectors. The plan was to use a NI-9758 (not purchased yet) to drive the four fuel injectors, and if the current demands of the coils were too high, then a high-speed solid-state relay between each channel could be used to isolate and reduce the current demand. The NI-9758 appears to be rated for 1.5 A per channel (continuous duty) and the high-pressure gasoline fuel injector solenoid drew up to 6.1 A during our testing, so it is likely that the SSRs will be needed.



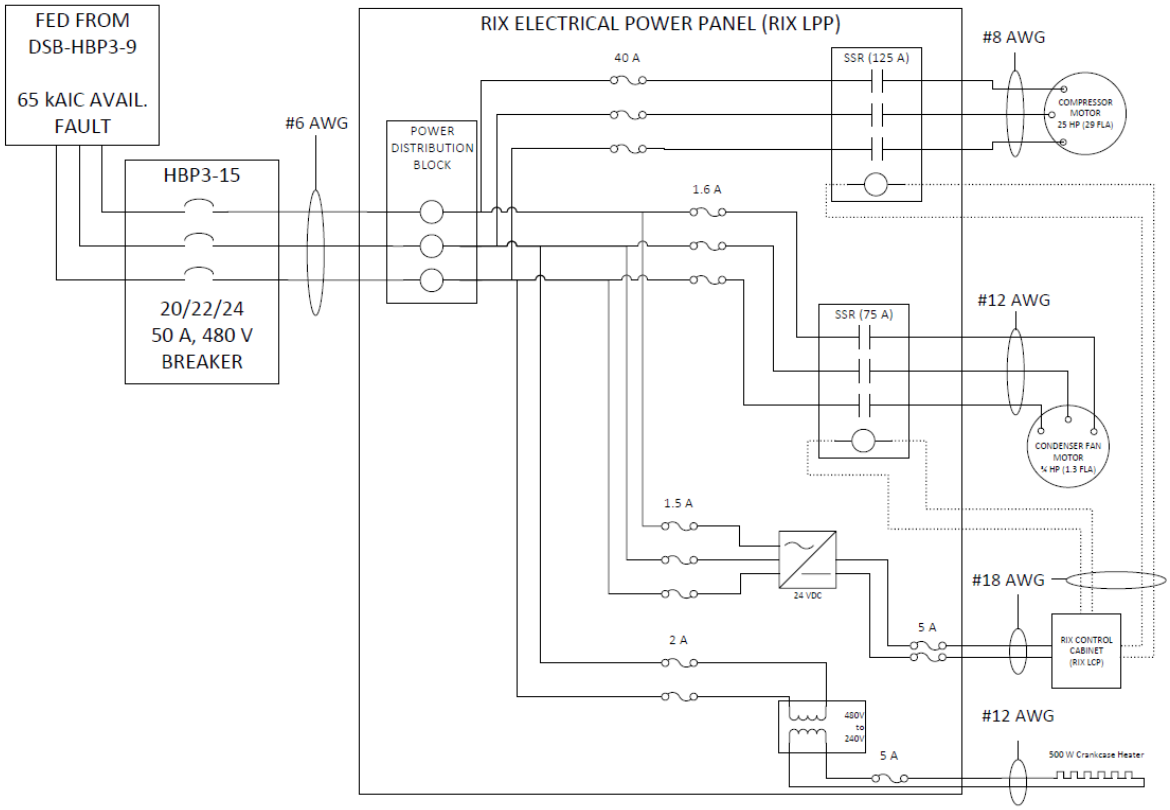
Initial testing was planned to be a simple LabVIEW VI run at high speed to provide pulse width modulation of the injector, however nothing has been programmed yet. Control programming the NI-9758 should be relatively straight forward, as it is designed for fuel injector control specifically. The three outlet fuel injector channels would be driven in parallel with one another, and the primary inlet fuel injector timing would be offset from them. For feedback and data collection, the plan was to use the high-speed pressure transducers embedded in the compressor cylinder head (provided by RIX) to allow for pressure measurement. The idea was to modify the pulse length, timing, and possibly even use multiple pulses to recreate the compression stroke pressure profile based on experimentally measured data. It would be something to experiment with as you go, but programming changes should be quick and easy to implement.

Specifications of recommended high-pressure gasoline fuel injector:
Manufacturer: Bosch
Model: 0261500109
"Type" (generic model grouping): HDEV-5-2LS
Pressure rating: Should be at least 200 bar based on other HDEV 5.2 ratings but could be as high as 500 bar depending on the model. The issue is that we don't have hard numbers (stamped on the side) for this metric. We only pressurized up to 1,500 psig nitrogen pressure during our tests. It is likely worth a hydrostatic test to failure before hydrogen applications (they are <$100 per unit, so it is cheap to test one to failure). See included documents and links.
Experimentally measured flow coefficient (stock): 0.042
Experimentally measured flow coefficient (tip ground down): 0.058
Coil drive voltage: 12 VDC
Coil drive amperage: approximately 5.8 – 6.1 A
Our purchase location: https://www.amazon.com/Bosch-Original-Equipment-0261500109-Gasoline/dp/B00H2RNZUG/ref=pd_sbs_263_1?_encoding=UTF8&pd_rd_i=B00H2RNZUG&pd_rd_r=bd392177-a0b6-11e8-ab81-4d3365da3b1b&pd_rd_w=hkVfR&pd_rd_wg=eWM9B&pf_rd_i=desktop-dp-sims&pf_rd_m=ATVPDKIKX0DER&pf_rd_p=7526152589566634282&pf_rd_r=35ZXGZG9XDW7TH4QKVT2&pf_rd_s=desktop-dp-sims&pf_rd_t=40701&psc=1&refRID=35ZXGZG9XDW7TH4QKVT2
Image:

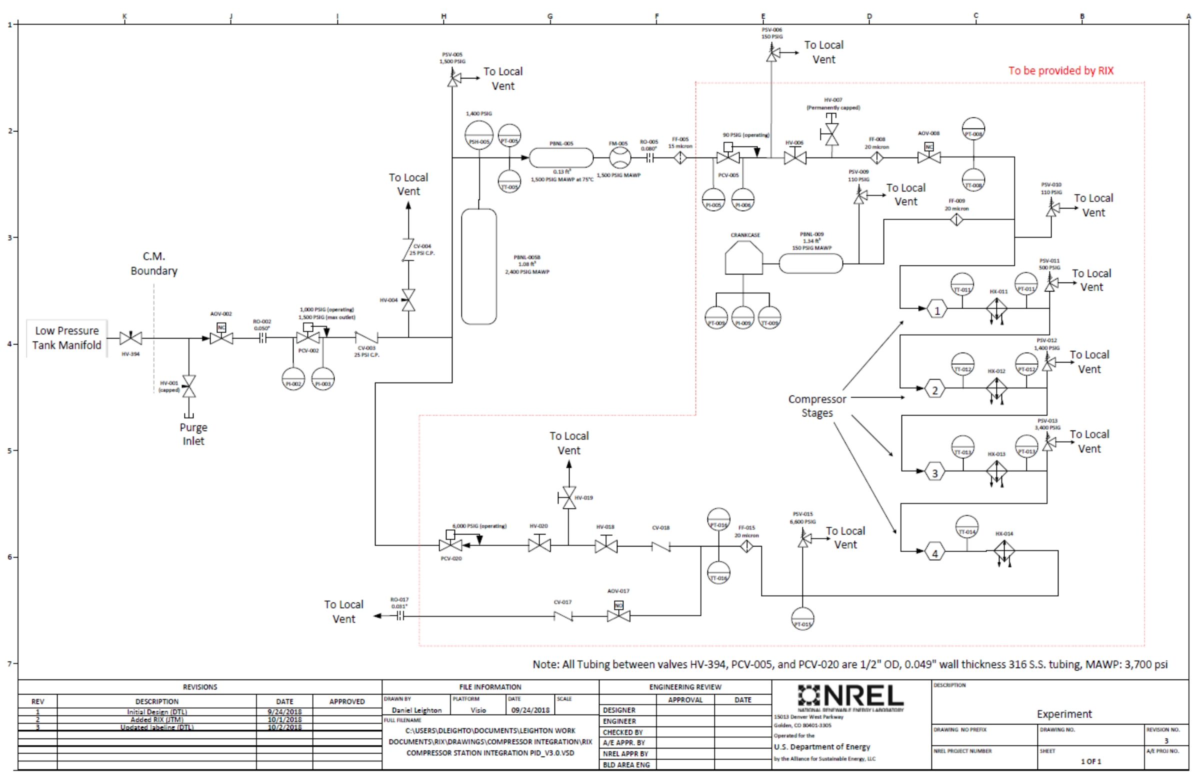
Fitting type: M12x1.5 DIN Metric Male Swivel
Fittings we purchased
https://www.discounthydraulichose.com/9197-04-L06-12.html
https://www.discounthydraulichose.com/6506-04-04-14-nptf-female-x-14-jic-female-swivel.html
And a ¼" MNPT to 3/8" tube connection to make the adaptation from the fuel injector to our nitrogen regulator.
At least 3 more sets of these fittings (or similar ones) would be needed for the additional fuel injectors used in the full system configuration.
Notes:
We only powered the coil for brief periods of time (<2 s) with the nitrogen pressurized to prevent overheating. We never had issue with it. For the diesel injector we had, it drew far more current (>20 A), and we may have damaged the coil from overheating (within a few seconds). Both types of fuel injectors use the injected fluid to help provide cooling of the coil, but the diesel unit seemed to be more sensitive. Keeping in mind that these injectors are typically mounted with thermal conductive contact to hot combustion engine blocks, it is our assumption that there is reasonably high heat tolerance. If during actual long-term testing, it becomes an issue, it should be relatively easy to provide simple air or liquid cooling to the coil portion of the unit.

Task 3: Performance and Efficiency Testing

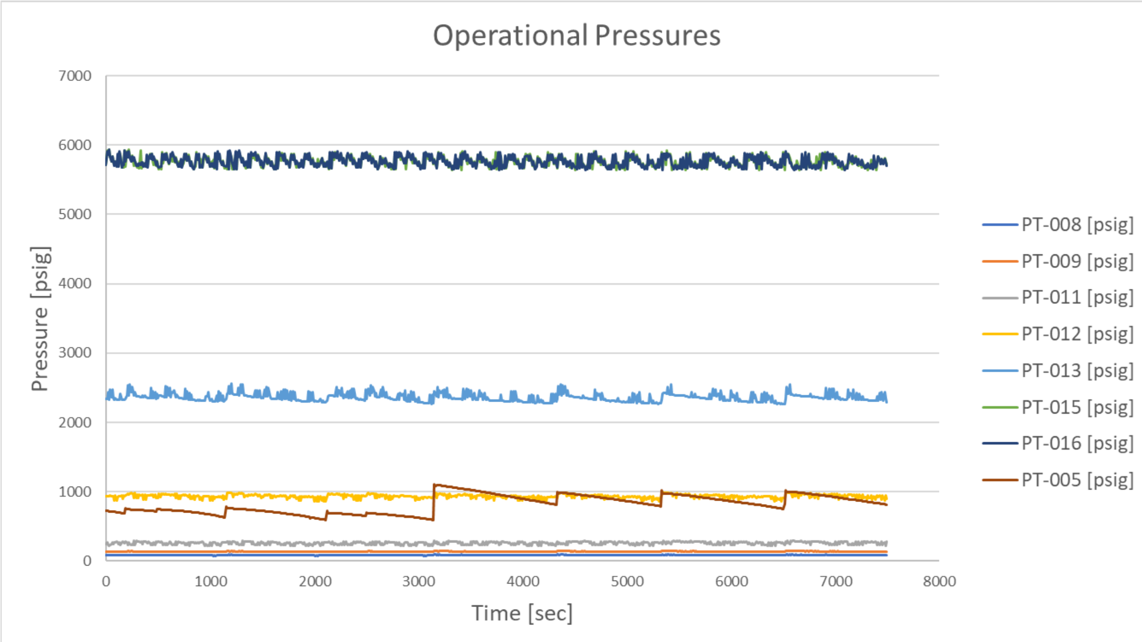
Task 3 was nearly fully completed by NREL from a labor and equipment cost perspective. Full system design, controls programming, station integration, safety evaluation, construction, and commissioning were completed for the compressor system at the NREL station (see picture of completed system installation below, high-voltage electrical system design, and station integration P&ID). The system was designed and configured to allow unattended operation for long-term durability testing with minimal labor input. RIX Industries representative Jason Thomas was on-site at NREL during start-up and initial operational data was collected for electrical efficiency, compression stage pressure and temperature levels, in-cylinder operational pressure levels, and cooling effectiveness. This high-speed data was provided to RIX Industries. Two plots from the limited data set show operational pressures and temperatures for the compressor below.

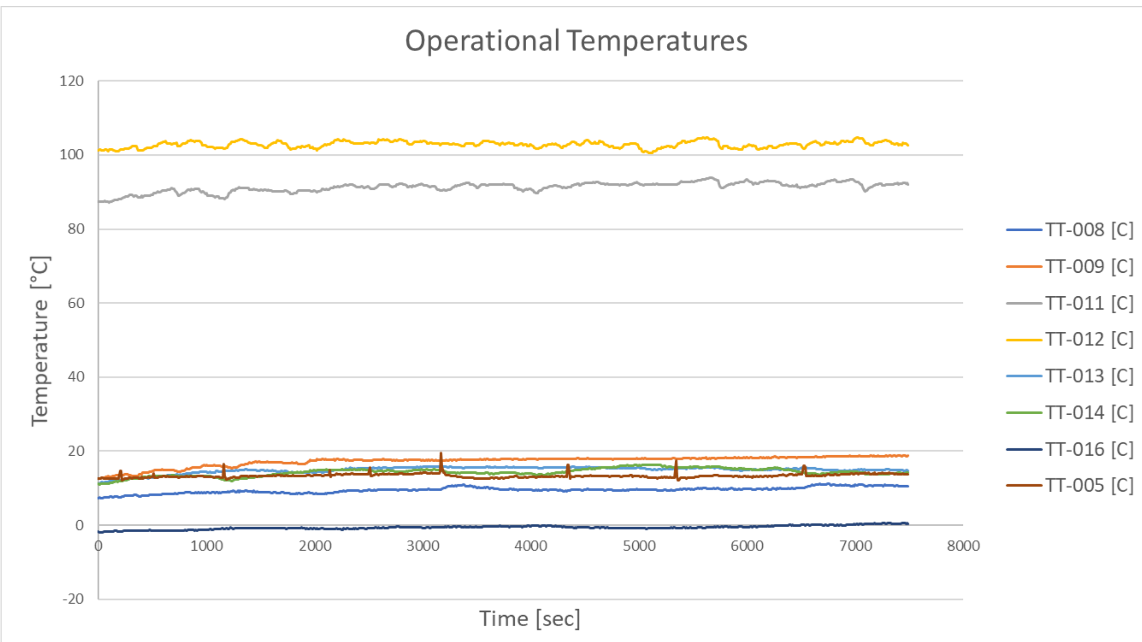


FED FROM DSB-HBP3-9
65 kAIC AVAIL. FAULT
HBP3-15
20/22/24 50 A, 480 V BREAKER
#6 AWG
RIX ELECTRICAL POWER PANEL (RIX LPP)
POWER DISTRIBUTION BLOCK
40 A
SSR (125 A)
#8 AWG
COMPRESSOR MOTOR 25 HP (29 FLA)
1.6 A
SSR (75 A)
#12 AWG
CONDENSER FAN MOTOR ¾ HP (1.3 FLA)
1.5 A
24 VDC
#18 AWG
5 A
RIX CONTROL CABINET (RIX LCP)
2 A
480V to 240V
5 A
#12 AWG
500 W Crankcase Heater



To Local Vent
To be provided by RIX
C.M. Boundary
Low Pressure Tank Manifold
Purge Inlet
Compressor Stages
Note: All Tubing between valves HV-394, PCV-005, and PCV-020 are 1/2" OD, 0.049" wall thickness 316 S.S. tubing, MAWP: 3,700 psi
REVISIONS
REV
DESCRIPTION
DATE
APPROVED
1 Initial Design (DTL) 9/24/2018
2 Added RIX (JTM) 10/1/2018
3 Updated labeling (DTL) 10/2/2018
FILE INFORMATION
Daniel Leighton
Visio
09/24/2018
C:\USERS\DLEIGHTO\DOCUMENTS\LEIGHTON WORK DOCUMENTS\RIX\DRAWINGS\COMPRESSOR INTEGRATION\RIX COMPRESSOR STATION INTEGRATION PID_V3.0.VSD
ENGINEERING REVIEW
APPROVAL
DATE
DESIGNER
ENGINEER
CHECKED BY
A/E APPR. BY
NREL APPR BY
BLD AREA ENG
NREL
U.S. Department of Energy
Experiment
1 OF 1





However, the full 2,000 hours of desired run time data via unattended operation was not completed. Less than 30 hours of runtime was completed – so no degradation data over time was collected, only initial performance data. This occurred because the project was put on hold just after start-up due to identification of material incompatibility in the RIX Industries provided compressor design by NREL following a station-wide detailed material compatibility safety review prompted by an unrelated material compatibility issue at the NREL hydrogen station. It is important to note that there was no safety incident or equipment failure related to the RIX Industries compressor (this project), this detailed review was only prompted by an unrelated issue at the station. After a few months of evaluation between the NREL and RIX Industries team, it was finally decided by RIX Industries that the safety factor margin was insufficient in their current design to be comfortable that it met the requirements of NREL's newly updated best practices for hydrogen material compatibility. At that point it was jointly agreed that the testing be cancelled and the project concluded, as a major compressor system redesign will be required for RIX Industries to provide a compressor with the desired design safety margin.

The compressor system and all parts/components provided by RIX Industries to NREL were shipped back to RIX Industries at their cost at the conclusion of the project, as originally agreed upon in the CRADA.

Task 4: Final Report

A copy of the final report for the compressor valve test apparatus design that was provided to RIX is included in the above "Task 1 & 2" section for the DOE and the public. It was decided that a more detailed report was not to be submitted for any journal or conference papers due to the lack of a working prototype, making the available material insufficient.

For the compressor testing portion of the project, this report will serve as the final report for the task, since long-term durability data was unable to be collected due to material compatibility issues that arose during testing. The lack of long-term durability data limits the value of a more detailed report.

Subject Inventions Listing:

None

ROI #:

None

Responsible Technical Contact at Alliance/NREL:

Daniel Leighton | Daniel.Leighton@nrel.gov

Name and Email Address of POC at Company:

Jason Thomas | jthomas@rixindustries.com

DOE Program Office:

Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Program