WATER RECOVERY FROM ENGINE EXHAUST

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1) Introduction

The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) and the Defense Advanced Project Agency (DARPA) are partnering to develop fundamentally new water technologies to reduce the logistics footprint and enable the development of a decentralized water support concept. The individual soldier requires 1.5 to 3.5 gallons per day to prevent dehydration. When personal hygiene, meal rehydration, and emergency medical treatment are included the daily planning factor becomes 4.1 gal per soldier per day. Current state-of-the-art water purification equipment can purify any source of water, but this potable water must then be transported from the source to the point of use on the battlefield. Without advances in water sustainment technology, water distribution is projected to account for 30 to 40% of the Objective Force daily sustainment requirement. TARDEC and DARPA are developing a range of revolutionary technologies for water recovery and generation. These technologies will produce water anywhere on the battlefield, thereby enabling the development of distributed water production systems to augment the soldier's water supply and significantly reducing the frequency and quantity of resupply. The technology will provide military units with a radically more mobile and flexible water production capability. The technology will enable future sustainment concepts allowing units to operate without external resupply for 3 to 7 days.

One of the most promising concepts under development is the recovery of water from internal combustion engine exhaust. The exhaust of internal combustion engines is a potential source of water on the battlefield. The primary combustion products of diesel fuel are water and carbon dioxide:

$$C_{12}H_{26} + 13.5\ O_2 \rightarrow 13\ H_2O + 12\ CO_2$$

Theoretically, one (1) gallon of diesel fuel produces approximately one (1) gallon of water. In exhaust emissions this water is in the vapor phase and mixed with numerous other compounds, most of which would be harmful to a soldier's health if consumed. Therefore, this water is not available to the soldier and a significant resource is wasted. In order to produce potable water from engine emissions the water must either be condensed from the exhaust gas and then purified or separated from the contaminants in the gas and then condensed as a pure product. The approach selected for this project was to condense the water out of the exhaust gas and then purify the condensate to meet drinking water standards to provide an alternative water source for the soldier. The condensate contains oxides of nitrogen and sulfur from the combustion process that make the water very acidic, as well as, soot particles, unburned hydrocarbons, metals, and other contaminants from the fuels, oils, and engine/exhaust wear or corrosion.

A Small Business Innovation Research Project was initiated by TARDEC in 1998 to evaluate the feasibility of creating drinking water from HMMWV exhaust. The LexCarb On-board Water Recovery Unit consists of a thin channel counter-current heat exchanger and chiller/demister unit mounted on the back of a HMMWV to condense and collect the water from the exhaust (Figure 1). The condensate is then pumped through a purification cartridge containing filtration, activated carbon and ion exchange resin materials to remove the contaminants from the combustion process to produce potable water.

2. Water Recovery

To recover water from combustion engine exhaust gas the exhaust gas stream must be cooled below the dew point, thus initiating condensation. The quantity of water collected is dependant on the amount of exhaust gas treated and the difference between the mass of water in air at the exhaust gas dew point entering the system and the mass of water in saturated air at the temperature exiting the chiller. The cooling energy that must be provided is the sensible heat to cool the exhaust gas from the inlet temperature to the desired temperature to recover a desired percentage of the water available plus the latent heat of condensation, approximately 1000 BTU/pound of water. The cooling is accomplished by passing the exhaust gas through a heat exchanger followed by a condenser (Figure 2). During the project a number of different variations have

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14. ABSTRACT

The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) and the Defense Advanced Project Agency (DARPA) are partnering to develop fundamentally new water technologies to reduce the logistics footprint and enable the development of a decentralized water support concept. The individual soldier requires 1.5 to 3.5 gallons per day to prevent dehydration. When personal hygiene, meal rehydration, and emergency medical treatment are included the daily planning factor becomes 4.1 gal per soldier per day. Current state-of-the-art water purification equipment can purify any source of water, but this potable water must then be transported from the source to the point of use on the battlefield. Without advances in water sustainment technology, water distribution is projected to account for 30 to 40% of the Objective Force daily sustainment requirement. TARDEC and DARPA are developing a range of revolutionary technologies for water recovery and generation. These technologies will produce water anywhere on the battlefield, thereby enabling the development of distributed water production systems to augment the soldier?s water supply and significantly reducing the frequency and quantity of resupply. The technology will provide military units with a radically more mobile and flexible water production capability. The technology will enable future sustainment concepts allowing units to operate without external resupply for 3 to 7 days.

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been tested. There were two significant configurations tested, the first was an air to air heat exchanger using fan power to provide ambient air to cool the exhaust followed by a condenser. The condenser was based on a standard commercial HMMWV air conditioning system with the evaporator installed in a demister following the air to air heat exchanger where the water was condensed and collected. The second configuration was a recuperative or counter current heat exchanger consisting of alternating thin channels separated by thin foils. In this configuration the hot exhaust gas passed through the heat exchanger where it was precooled by chilled exhaust gas leaving the condenser, then passed through the condenser where the exhaust gas was further cooled and water condensed, then returned back through the heat exchanger where a significant portion of the cooling energy was recovered. The dew point of the exhaust gas was estimated to be 100 to 110 degrees F for the design operating range assuming the 160 horsepower engine operating at 70% of the maximum rpm and 70% load with the dew point of the inlet air to the engine at 40 degrees F (approximating desert conditions of 120 degrees F and 10% relative humidity). The required temperature the exhaust gas must be cooled to assuming saturation was then calculated for various recovery efficiencies ranging from 50 to 70%, with recovery defined as the gallons of water produced per gallon of fuel consumed. A heat exchanger was designed based on the calculations and preliminary measurements of the temperature and flow of the exhaust gas. Over 171 experimental runs were conducted with various systems to determine the temperature and water content of the exhaust under different operating conditions and to evaluate the performance of different configurations under design conditions.

Figure 1. LexCarb On-Board Water Recovery Unit (OBWRU)

2.1 Water Collection Demonstrators

The first version of the On-Board Water Recovery Unit to be tested consisted of intercooler type air to air heat exchanger connected to a demister to collect the water with the chiller (GM Van rear AC chiller #1254-3631) installed inside the demister to minimize size. Both the intercooler and chiller were fabricated of aluminum coated with heresite, a commercially available phenolic resin that is resistant to corrosion. The system was instrumented with thermocouples and temperature measurements were taken from 15 different locations, as well as 2 pressure measurements. 120 different test runs were conducted in this basic configuration with different heat exchangers and demister components to evaluate their performance and define the optimum characteristics of these components with respect to minimizing size and maximizing water production. Water production was characterized both in terms of pounds per mile and gallons of water produced per gallon of diesel fuel consumed. The test runs were designed to evaluate the effects of operating conditions on water production, water quality and system impact on vehicle performance. Table 1 shows the results for a series of runs with the smallest intercooler and demister combination tested. The intercooler in this configuration was 35.5” long by 13.75 inches high and 2.75 inches wide and the demister was 9.5 inches long by 9.75 inches wide and 13.5 inches high. Two different sets of run conditions were tested, constant speed at 50 mph and variable speed at 5-50-5. Most reported runs were performed at steady speed although due to road conditions there was some acceleration and slowing down. A simple cycle was used to simulate water production from the engine operating under a variable load and speed. Nominally the acceleration was at about 2/3 of maximum from 10 ± 5 mph up to 50 mph during which time the engine revs varied mainly between 2,000 and 3,000 in 2nd and 3rd gears. On reaching 50 mph the vehicle was allowed to slow with the accelerator released to 10 ± 5 mph then the cycle was started again. Under these conditions around 11 ± 0.8 mpg was achieved, at an average speed of 36 ± 2 mph. Water yields, with fans and chiller running continuously, were fairly constant for runs which exceeded 20 miles. The inlet temperature to the chiller was maintained above the dew point of the exhaust gases (~105ºF). All condensation therefore took place in the chiller. The water yields for the two different sets of run conditions were the following:

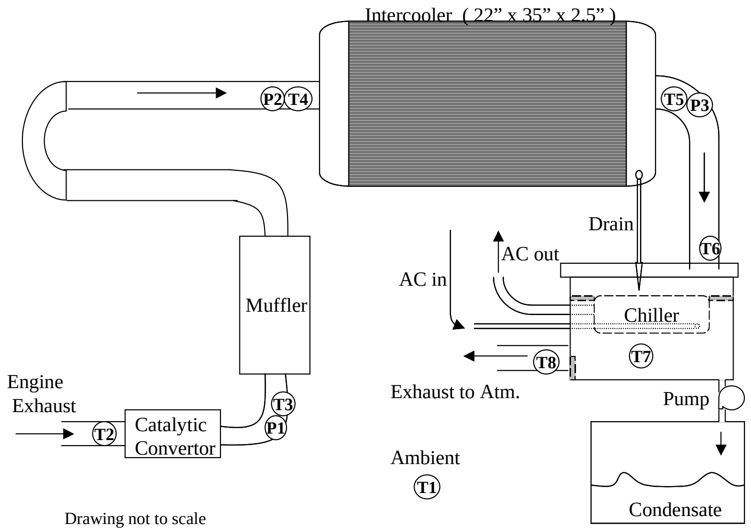

Figure 2 Schematic of water collection system

- At Steady 50 mph, 2000 rpm
  - No condensation before chiller
    - 16 ± 1 lbs/hr
    - 33 ± 3 lbs/100 miles
    - 0.58 ± 0.02 gal/gal fuel 61 ± 3% of “fuel” water
    - 46-62% of total water in exhaust
- At Average Speed, 35 mph, 5-50-5 mph (High Load, Coast)
    - 17 ± 1 lbs/hr
    - 58 ± 4 lbs/100 miles
    - 0.74 ± 0.02 gal/gal
    - 75% of “fuel” water

On a steady 50 mph run the water yield was 30-35 lbs/100 miles, which was lower than the water yield achieved under high loads (5-50-5 test) at 58 lbs/100 miles. The high condensate yield in gal/gal was encouraging considering the variability in the actual load and illustrates that at high load and high rpm the system still coped without significantly reduced efficiency.

2.2 Fuel Consumption Analysis

To determine the effect of the OBWRU (On-Board Water Recovery Unit) on fuel consumption, data from runs with and without the OBWRU were analyzed. The runs conducted range from 60% - 90% engine load. The OBWRU caused the fuel consumption to increase by 0.42 to 0.45 gal/100 miles regardless of speed or vehicle weight. Based on the water production rates described in the previous section this results in a ratio of water produced per gallon of extra fuel consumed of 8:1 to 15.5:1 gal/gal. Thus, under representative field conditions, the change in fuel consumption would be only 4%, from 9 mpg (11.1 gal/100 miles) to 8.6 mpg (11.6 gal/100miles) with the OBWRU. The added energy requirements of the OBWRU were due primarily to the energy required to run the chiller system, the back-pressure effects, and the added weight. On the basis of the tests described so far we would predict that at 120°F and 10% RH we could produce 1.8 gal/hour of water when the vehicle engine was running at 2,300 rpm at half power. The fuel consumption would be 4.2 gal/hour for motive power etc and 0.35 gal/hour extra for the water production unit. This could be at 60 mph in top gear on flat good roads, or at ~ 40 mph in 3rd gear over undulating countryside.

Run #	miles water collect.	Fuel cons (mpg)	water amounts (lbs/mile)					Yield per gal diesel (gal/gal)	Dew Point air in (°F)	Dew Point engine exh. (°F)	Temp. IC out (°F)	Calc. Dew Pt. of chiller outle (°F)	Temp. Chiller Outlet (°F)
			in fuel	air in	total in	actual yield	in outlet total - yield						
Steady 50mph runs													
W86	84.7	14.8	0.56	0.07	0.62	0.34	0.28	0.61	32	98	104	72	79
W90	84.9	14.1	0.58	0.18	0.76	0.35	0.41	0.59	55	105	110	84	82
W91	86.0	14.5	0.56	0.15	0.71	0.36	0.35	0.63	54	102	106	80	85
W92	86.8	14.5	0.56	0.15	0.72	0.31	0.41	0.53	53	102	113	84	80
W93	2.5	14.5	-	-	no water collected			-	54	102	95	-	-
W94	84.8	16.5	0.50	0.06	0.56	0.03	0.53	0.05	32	95	-	93	-
W95	84.8	14.7	0.56	0.10	0.66	0.34	0.32	0.61	43	95	-	76	-
W96	84.6	14.7	0.56	0.10	0.65	0.33	0.32	0.58	40	101	-	76	-
W97	84.9	14.8	0.55	0.05	0.60	0.32	0.27	0.58	<32	101	103	72	90
W100	84.9	14.5	0.57	0.02	0.58	0.36	0.22	0.63	<32	96	100	64	83
W101	84.9	15.1	0.54	0.02	0.56	0.32	0.25	0.58	<32	94	108	68	85
5 - 50 -5 mph runs													
W87	6.5	11.0	0.74	-	no water collected			-	58	-	95	-	94
W88	6.5	12.4	0.66	-	no water collected			-	60	-	131	-	87
W89	52.2	10.8	0.76	-	-	0.59	-	0.77	60	-	127	-	70
W98	30.6	10.1	0.81	-	-	0.55	-	0.67	<32	-	79	-	70
W99	22.6	10.2	0.80	-	-	0.76	-	0.93	<32	-	80	-	63

Table 1: Water Yields and Dew Points for Different Water Collection Runs

3 Exhaust Condensate Purification

The primary project objective was to produce drinking water from the exhaust condensate that met the tri-service long term consumption quality standards specified in the Technical Bulletin Med 577 Occupational and Environmental Health: Sanitary Control and Surveillance of Field Water Supplies. Water quality analysis identified soot particles, polar and non-polar organics, and metals in the exhaust condensate. The approach selected contended that these contaminants could be removed through an appropriate combination of filtration (to remove solids), adsorption on activated carbon (to remove organics and some inorganics), and ion-exchange resin (to remove ionic species). The initial treatment train consisted of filtration, an activated carbon fiber monolith (ACF), and ion exchange resin material.

3.1. Soot/Particle Filtration Studies

The concentration of fines in the exhaust condensate ranged from 20-970 ppm, or 20-240 mg/gallon of diesel combusted. Factors that affected soot formation were load and engine rpm, with the concentration depending on the amount of condensate yield. Condensate samples were collected during acceleration and deceleration of the vehicle. The highest levels of solids were collected during the acceleration stages i.e. 0-50, 0-60 and 50-60 at 85, 71 and 49 ppm respectively. The lowest level, 20 ppm, was during the deceleration period from 60 – 50 even though much of this period would have been at a steady 50mph. The steady speed runs were remarkably consistent at an average of 31 ppm for runs at 50mph and 60mph. The solids levels in all samples were less than for the hard acceleration/slowing 5-50-5mph cycles where 100+ ppm was the norm. These fines, down to sub-micron size, had been filtered out using commercially available 2 micron glass fiber papers at a few psi differential. The rates observed indicated that only about a square foot of filter area would be needed to cope with the 180 gallons of condensate at rates always in excess of 2 gal/hr. Filtrations have been performed both in the laboratory and on-board the HMMWV demonstrating solids removal down to sub micron level in size (to less than 1 ppm), which would require a filter area of 0.5 ft^2 (3" diameter cylinder 8" long) unpleated that would cope with 180 gallons of condensate at the required flow rate, i.e. 2 gals/hr plus throughout its life.

3.2 Exhaust Condensate Composition

After the water had been filtered to remove soot particles, it still had a distinct brownish/yellowish color due to organic/inorganic contaminants, Figure 3. The condensates were numbered as the water collection run number with an F attached if it has been particle filtered, i.e. W3F, W15FF. The carbon-filtered samples have a carbon run number at the end, i.e. W8FC9; the ion exchange filtered samples have the resin filtration run number at the end i.e., W10FC9R1.

Exhaust condensate Particle Filtered Water Carbon/Resin Purified WaterFigure 3: As-received and purified exhaust condensate

3.2.1 Organics Content of Condensate

The total organic carbon (TOC) content of the exhaust condensate was found to be the most significant parameter in design of the water purification unit. High TOC contents require larger beds of carbon and ion exchange resins. The TOC content in the water collected in Phase I varied from 60-260 ppm and in Phase II it has been as high as 360 ppm. The primary factors affecting the TOC concentration of the condensate were exhaust system temperature, water yield, engine load and age of catalytic converter. Higher concentrations of contaminants were found at the higher condensate collection temperatures. When no chiller was used the temperature varied from 77-94°F and the condensate yield was lower than in most of the previous runs (0.12-0.33 lbs/mile), which resulted in higher contaminant concentrations.

The HMMWV had 104,000 miles on the odometer when purchased. It appeared that the performance of the catalytic converter was not optimum due to the high mileage, and the TOC content of the exhaust condensate was higher than it would be for a new system. In order to elucidate the influence of the catalytic converter performance on TOC content the catalytic converter was removed for a series of runs. The TOC content of condensates produced with the original catalytic converter and without the catalytic converter are shown in Figure 4. The TOC content was five times higher for the 5-50-5 runs without the catalytic converter, but it made little or no difference to the steady 50 mph runs. Installing the brand new catalytic converter halved the TOC concentration of the condensate for all types of runs, the 50 mph, 60 mph and 5-50-5 mph, when comparing to the runs with the original catalytic converter (104,000-118,000 miles on the odometer). When the TOC results from the runs with the new catalytic converter were compared with the results from Phase I where the vehicle had 41,200 miles on the odometer, the TOC was reduced by about 30% by installing the new converter. Since the new catalytic converter was installed, the TOC contents varied between 46 to 158 ppm. Analysis of the organic compounds in the exhaust condensates were performed by EnviroData Group, LLC in Lexington, KY according to EPA's water analysis techniques. Volatile organics are determined by technique EPA 524.2 and semi-volatiles by EPA 525.2. The identified contaminants included: benzene, styrene, naphthalene, trichlorofluoromethane, 1,2,4 and 1,3,5-trimethyl benzene, acrylonitrile, 2-butanone, epichlorohydrin, tert-butyl alcohol and vinyl acetate, di (2ethylhexyl)pthalates, acenapthylene, isophorone, 1-methyl-napthalene and 2-methyl-napthalene, phenantrene and an unknown hydrocarbon oil. The identified compounds only added up to a total organic content of 3 ppm. This was significantly less than the TOC of 100 ppm indicating the tests did not identify many impurities in the condensate. Several additional tests were performed in an attempt to identify the unknown compounds. These tests included total phenol content, and a test for traces of diesel and motor oil. Phenol was identified in the condensate at concentrations of up to 0.49 ppm, while the content of compounds related to diesel was 13 ppm and the concentration of ones related to motor oil were 19 ppm. It was obvious that there were organics in the water that were not quantitatively determined by the standard drinking water techniques. A high-accuracy organic analysis was therefore performed by Chemir laboratories using Solid Phase MicroExtraction (SPME) to concentrate the contaminants in the water before GC/MS analysis. A range of compounds were identified, however, the total concentration of these compounds were still below the total of 100 ppm. From both sets of analysis it can be seen that the samples contain a wide range of organics including aromatics, phenols, aldehydes and ketones.

3.2.2 Inorganic Content of Water

The pH of the contaminated water was measured at the time of collection using a handheld pH meter. The pH of the condensate ranged from 2.4 to 2.9. The most significant inorganic contaminants were nitrates, nitrites and sulfates that form during the combustion process when nitrogen present in the air and sulfur present in the fuel react with the oxygen in the air. The nitrate level ranged from 7.1 to 34 mg/L and the nitrites ranged from 0.13 to 4.28 mg/L. The concentration of nitrate exceeded the maximum contaminant level (MCL) of 10 mg/L and the nitrite concentration exceeded MCL of 1 mg/L in a number of cases and will, Therefore, need to be removed. The sulfate content ranged from 140 to 270 mg/l and exceeded the drinking water MCL of 250 mg/L in some instances and will also need to be removed in order to produce potable water. The phosphorus concentration was found to range between 0.05 and 0.32 mg/L.

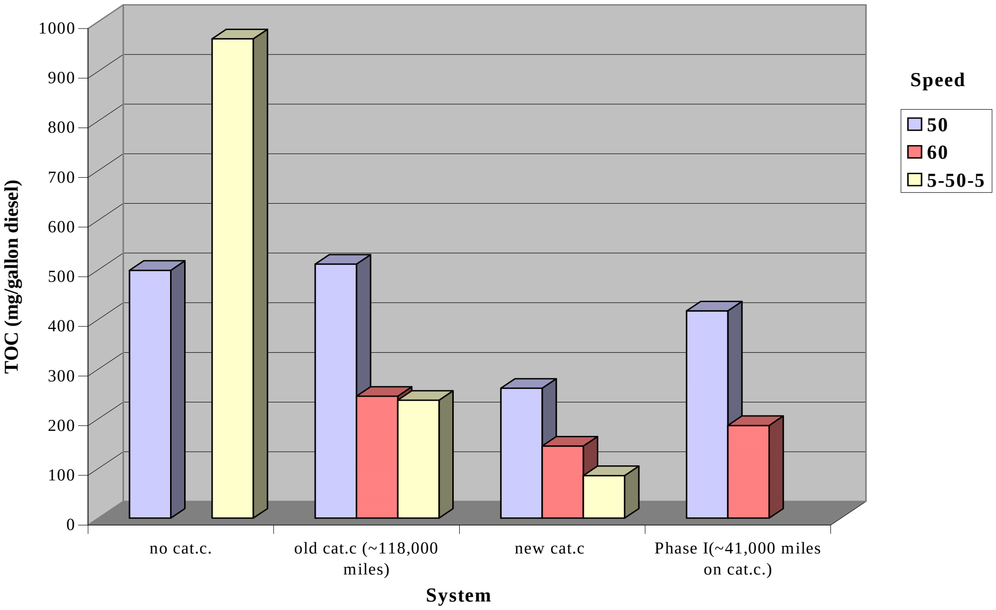

Figure 4: TOC concentration of condensates produced with different catalytic converters.

Representative values of the metals concentration of the different condensates produced in several runs with the air to air intercooler type OBWRU are shown in Table 2. In summary for all runs conducted, the main contaminants were:

- Aluminum: 2-330 ppm - from Heresite-coated aluminum heat exchanger
- Boron: 0.3-9 ppm -biocide, additive to diesel
- Zinc:0.5-1.5 ppm
- Iron:2.4-3.7 ppm – wear/corrosion from engine/exhaust pipe

In addition there trace amounts of Cu, Ca, Mg, Mn, Mo and Ni. The combined concentration of all non-Al metals was less than 10 ppm. The metals of most significant concern were aluminum and boron. The high aluminum content was due to the materials used in the construction of the heat exchanger. The air to air type heat exchanger used was made from different variations of TCT aluminum intercoolers coated with Heresite to prevent corrosion. Due to the high temperature in the exhaust system, the coating cracked after a period of operation, resulting in corrosion and high aluminum content in the exhaust condensates. This problem may be addressed by the selection of materials for the OBWRU. Other potential sources of metals were diesel fuel additives and wear of metal engine parts. An analysis of the fuel used during testing identified significant concentrations of Silicon (7.1 mg/L), Boron (2.2 mg/L), and Magnesium (0.7 mg/L).

Compound	**MDL**	**Units**	**collected**			**Purified**						**MCL**
			W3-1	**W3-B**	**W15FF**	**W8F**	**W9F**	**W9F**	**W9F**	**W12F**	**W14D**	
						C9	**C10R1**	**C10R2**	**C10R3**	**C13R7**	**C14R8**	
Chloride	1	mg/L	1		BDL	6	BDL	BDL	BDL	BDL	BDL	250
Fluoride	0.20	mg/L	3.28	4.14	4.5	2.61	BDL	BDL	BDL	1.69	14.2	2
Nitrogen, Nitrite	0.01	mg/L	0.21	0.21	BDL		BDL	BDL	BDL	0.02	BDL	
Nitrogen, Nitrate	0.1	mg/L	1.2	1.3	2.5		BDL	BDL	BDL	BDL	BDL	
Sulfate	1	mg/L	56	45	310	91	BDL	BDL	BDL	-	BDL	250
Hardness, Calcium	1.3	mg/L CaCO3	2.9	6.1	-	2.9	BDL	BDL	BDL	-	BDL	
Color (CoPt)	5	CoPt Units	35	35	-	10	BDL	BDL	BDL	-	BDL	15
Corrosivity-Langelier Saturation Index	0.1	pH Units	0.1	0.1	-	-3.3	-5.5	-5.4	-5.5	-	-3.2	
Hardness, Total	1	mg/L	5	7	BDL	4	BDL	BDL	BDL	-	BDL	
Total Mercury (Cold Vap)	0.0002	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Silver (ICP)	0.01	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	
Total Aluminum (ICP)	0.05	mg/L	4.0	7.7	70	22	BDL	BDL	BDL	BDL	BDL	
Total Arsenic (ICP)	0.05	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Barium (ICP)	0.01	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Beryllium (ICP)	0.002	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Boron (ICP)	0.05	mg/L	0.58	0.59	0.31		BDL	BDL	BDL	3.8	0.21	
Total Calcium (ICP)	0.5	mg/L	1.2	2.4	2	1.3	BDL	BDL	BDL	BDL	BDL	
Total Cadmium (ICP)	0.005	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Cobalt (ICP)	0.02	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Chromium (ICP)	0.01	mg/L	0.04	0.05	0.02		BDL	BDL	BDL	BDL	BDL	
Total Copper (ICP)	0.005	mg/L	0.11	0.15	0.1	0.11	BDL	BDL	BDL	BDL	BDL	
Total Iron (ICP)	0.05	mg/L	2.4	3.7	2.9	3.5	BDL	BDL	BDL	0.09	BDL	
Total Potassium (ICP)	0.5	mg/L	0.8	1.7	9.2		BDL	BDL	BDL	BDL	BDL	
Total Magnesium (ICP)	0.05	mg/L	0.26	0.12	0.26		BDL	BDL	BDL	BDL	BDL	
Total Manganese (ICP)	0.01	mg/L	0.03	0.09	1.2	0.16	BDL	BDL	BDL	BDL	BDL	
Total Molybdenum (ICP)	0.02	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Sodium (ICP)	2	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	3	
Total Nickel (ICP)	0.02	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Lead (ICP)	0.05	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Antimony (ICP)	0.05	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Selenium (ICP)	0.05	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Silicon (ICP)	0.5	mg/L	BDL	BDL	7.3		BDL	BDL	BDL	3.4	1.4	
Total Titanium (ICP)	0.005	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Thallium (ICP)	0.05	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Vanadium (ICP)	0.01	mg/L	BDL	BDL	BDL		BDL	BDL	BDL	BDL	BDL	
Total Zinc (ICP)	0.05	mg/L	0.50	0.94	1.5	1.4	BDL	BDL	BDL	BDL	BDL	
Surfactants, Anionic	0.012	mg/L MBAS	0.062	0.033	-	0.058	0.015	0.022	0.056	-	BDL	0.5
Odor	1	TON	39		-	9	-	-	-	-	-	
Phosphorus, Total	0.01	mg/L as P	0.23	0.26	0.17		0.04	0.03	0.03	0.02	0.03	
Total Cyanide	0.01	mg/L			-		BDL	BDL	BDL	-	-	
pH (Lab)	0.1	pH Units	3.0	3.2	-	7.2	5.5	5.6	5.8	4.8	7.7	
Solids, Total Dissolved	10	mg/L	48	88		207	BDL	BDL	BDL		24	500
Carbon, Total Organic	**0.5**	**mg/L**	**98**	**110**	**43**	**52**	**7.3**	**5.8**	**4.1**	**26**	**66**	
Total metals		mg/L	9.92	17.44	93.27	28.47	0	0	0	7.29	1.61	
Total inorganics		mg/L	61.92	50.91	317.2	99.61	0.04	0.03	0.03	1.73	18.63	

Table 2: Metals content of exhaust condensates

3.3. Design of Water Purification Train

A number of different water purification trains were tested to optimize the removal of contaminants identified in the exhaust condensate. Many commercial activated carbons were tested along with LexCarb's own activated carbon fiber composite materials. The different combinations of water filters making up the various purification trains will be discussed. Two different water samples were produced with TOC of 0.1 and 0.3 ppm respectively. The trace organic contaminants in the purified water were analyzed, and none were identified as hazardous through LexCarb's toxicology studies. The key problems from Phase I were boron content and pH control, which were overcome as well. However, large amounts of potable water have not yet been produced since the ion exchange resin was attacked by the condensate and started leaching organics over time.

3.3.1 Activated Carbon Treatment

After the particle filtration step the exhaust condensate was filtered through an activated carbon bed to remove any non-polar organic contaminants. The first adsorption columns were activated carbon fiber composites with a diameter of 1" and approximately 3.5" long. The approximate carbon weight was about 13 g and the composites had a cured density of about 0.48 g/cc. The composites were activated to carbon burnoff's of 36- 50%. A 1.6 micron glass fiber filter was placed at the end of the carbon filter to catch any fines. A flow rate of 16 ml/min or 960ml/hr was used for the small-scale study. In later experiments another breakthrough study was performed on an activated carbon fiber composite carbon bed that was 2" diameter x 5" long and the condensate flow rate was 32 ml/min. This study was based on starting exhaust condensate with a TOC content of 250 ppm. The TOC content of the column effluent started at 46 mg/L increased to 120 mg/L after treatment of 4 gallons then remained constant after filtration of 11 gallons. The carbon therefore removed greater than 50% of the organic contaminants. The conductivity and pH of the water increased rapidly during the first 3 gallons of water treated, then increased less from 4-10 gallons of condensate treated. The TOC after passing through the ion exchange resin bed, described later, varied from 4-12 mg/L suggesting that the resin was removing polar organic molecules which the carbon fiber would not be expected to remove. Since the ion exchange resin removed 110 mg/L of the remaining TOC it was probable that the carbon had some polar sites and some capability to take out metals from the water demonstrated by the removal efficiency during the first 4 gallons, but these sites saturated rapidly leading to the reduced removal efficiency from 4 to 11 gallons. The TOC data for the carbon filtration suggested that the breakthrough for nonpolar organics occurred after more than 11 gallons of exhaust condensate has been treated for a filter size of 2" diameter by 5" long. Based on these results the size of the carbon fiber composite canister needed for treatment of 180 gallons of water was estimated to be 5" diameter by 7-14" long for exhaust condensate with a TOC content of 250 ppm while the canister would be smaller if the exhaust condensate collected had a lower TOC content.

Since there was evidence of presence of large amounts of polar organics as well as large molecular weight carbon compounds in the filtrate, investigations were conducted on the use of alternative activated carbons. Although most activated carbons have neutral surfaces and do not remove polar molecules, there are commercial wood-based carbons and some coal-based ones that are more efficient in removing polar compounds than the activated carbon fibers. These carbons also have wider pore size distributions and more oxidized sites than the activated carbon fibers which would be more effective in removing the polar and large molecular weight compounds identified in the purified water samples. The activated carbon fiber composites had very narrow micropores and removed the smaller organic molecules like benzene.

The exhaust condensate was filtered through an activated carbon bed of 2" diameter x 5" long at a condensate flow rate of 16 ml/min. The initial condensate used in the filtration runs had a TOC of 250 mg/L. A coal based Granular Activated Carbon from the Calgon Corporation, normally used in water treatment was able to reduce the TOC from 250 to 45 mg/L for the first gallon of water treated and from 250 to 57 mg/L after the first gallon. A subsequent treatment of the coal-based carbon effluent with activated carbon fiber composite reduced the TOC from 45 to 42 mg/L, suggesting there was not a significant difference in the capacity or pore size distribution for the coal based carbon and the activated carbon fiber composite. A wood-based activated carbon from the Westvaco Corporation was used that only reduced the TOC to only 72 mg/L because it has a smaller amount of narrow micropores and was not as efficient in removing smaller organic molecules. However, when combined with the ACFC it lowered the TOC to 30 mg/L. This indicated that it was more efficient in removing some of the polar and larger molecules that the coal based GAC and composite did not remove. Even though the wood-based GAC produced good results for TOC it was not useable in its current form in the purification train at this stage since it released phosphorus into the water, which led to a rapid breakthrough of the ion exchange resin. Westvaco Corporation agreed to produce a wood based carbon with a low phosphorus content and a wide pore size distribution in their pilot plant for testing in the water purification train.

The next set of water purification studies were performed on a set of condensate samples produced during steady speed runs at 60 mph with the new catalytic converter. The TOC content of the combined sample from these runs was lower than for the previous tests at 58 mg/L. Three different carbon beds were tested, two carbon fiber composites and one bed of granular activated carbon. The carbon fiber composite reduced the TOC of the condensate from 58 mg/L to 16 mg/L. The GAC reduced the TOC further to about 8 mg/L. The GAC was also very effective in increasing the pH from 2.9 to a level varying from 9-4.5, Table 3. The composite did not affect pH except for treatment of the first 2 gallons, it then stayed constant at 3 which was similar to the untreated condensate. The GAC also reduced the conductivity significantly from 464 to about 75-150, Table 3, while the composite only reduced the conductivity to 300 for the first 5 gallons, then it remained similar to the condensate.

3.3.2 Ion Exchange Resin Treatment

Ion exchange treatment was selected to remove inorganic contaminants from the exhaust condensate. A variety of resins were selected based on their capacity to remove contaminants of interest for this project. The resin was packed into a column with a height of 12" and diameter 1" or 24" by 1" diameter. Water was pumped through the resin bed at constant flow rates in an upstream configuration. The flow rate through the bed was 32 ml/min or 0.85 gpmft^2. Resins tested were acquired from Rohm & Haas and Sybron and included; a gel type anion exchange resin in the OH- form, a mixed strong acid and base gel type ion exchange resin in the H+, OH- form, a resin designed to increase the pH of the water, and a resin formulated to remove nitrogen compounds.

The results demonstrated that the ion exchange resin was extremely effective in removing the metals and inorganics from the contaminated water. Of the range of metals that were present in the collected water, the highest concentration was aluminum at up to 97 mg/L. The ion exchange resin removed it to below detectable limits (BDL). The metal that could not be removed in the Phase I study was boron, which was present in the exhaust condensate at concentrations of 0.6 mg/L. With the ion exchange resin used in the current water treatment system, the boron was removed to BDL. All other metals identified in the exhaust condensate were also removed to BDL by the ion-exchange resin, Table 2. The inorganic compounds present were also removed to below detectable limits (BDL) with the exception of phosphorus at a concentration of 0.04 mg/L. This was well below the concentration in the collected condensate where it was present in concentrations up to 0.26 mg/L and does not present any health hazards. The compounds that were removed included chloride, fluoride, nitrites, nitrates and sulfates at concentrations up to 56 mg/L. In the first eight resin filtration runs, the pH of the condensate was about 5.5 after the filtration. Water pH control was a problem that occured when using strong acid and base type ion exchange resin for purification. The resins add H^+ and OH^- into the water when metals and inorganics are exchanged onto the functional groups of the resin. Therefore an anionic resin was added for pH control, which increased the pH to 6.34. In composite resin bed of 10" of a mixed strong acid and base gel type resin and ¾" of resin for pH control the pH was 6.82, which is acceptable for drinking water.

The ion exchange resin removed most of the polar organic contaminants remaining after carbon filtration. The TOC ranged from 4.3 to 7.1 ppm for the first 1.1 gallons treated then rose to 18 ppm after 1.8 gallons were treated suggesting that break through had occurred. While this was above the proposed regulation limit for drinking water of 2 mg/L, it was believed that the main cause for the elevated TOC number were organic compounds leaching from the ion exchange resin. Data from UV-VIS suggests that there are organic compounds added to the water during ion exchange resin filtration. The resin used in the experiments was designed to leach very low amounts (in the ppb range) of TOC, ionic species, and silica. However, oxidants can attack ion exchange resins and result in TOC release, particulate release, and loss of performance.

In order to minimize leaching from the ion exchange resins the flow rate through the resin was increased to 250 ml/min, which was ~50 bed volumes per hour and within the recommended range of 30-50 bed volumes per hour in subsequent runs. The results of the resin treatments are shown in Table 3. The GAC treated water was purer after the ion exchange resin than the carbon fiber composite treated water. The TOC ranged from 2.4-6 mg/L, pH from 8.1-8.9 and conductivity from 4-7μS/cm. Although improvements were still needed, drinking water was produced with a TOC of only 2.4 mg/L.

Table 3: TOC, pH and Conductivity of Drinking Water from Exhaust

Treatment Material	Sample ID	Volume (gal)	TOC (mg/L)	pH	Conductivity (uS/cm)
Starting Material	W103115		65	3.00	496.4
Calgon Carbon	C33A	0.69	8.078	8.86	36.67
TOG 20X50	C33B	1.39	7.957	8.31	62.3
	C33D	2.78	8.069	5.40	93.1
	C33G	8.04	7.214	4.48	146.7
	C33I	9.43	8.097	4.43	158.5
	C33K	10.82	9.914	4.31	211.3
	C33M	12.21	5.27	3.58	310
	C33O	13.48	4.64	3.30	319.1
UP6040 Resin	C33AR9A	0.61	2.346	8.35	5.28
	C33BR9B	1.26	4.682	8.56	7.17
	C33DR9D	2.59	5.589	8.18	3.80
	C33GR9G	3.91	5.100	8.46	5.85
	C33IR9I	5.24	5.979	8.41	6.02
	C33KR9K	6.62	3.941	8.89	6.63
Sybron Ionac	C33LR11A	0.61		5.25	129.7
A-554 Resin	C33MR11B	1.25	7.353	5.16	104.1
	C33NC34CR11C			4.79	68.6
UP6040 Resin	C33LR11AR12A	0.55			
	C33MR11BR12B	1.05	3.19	6.7	12.23
WestVaco	C33LR11AR12AC34A	0.51	1.489	6.43	7.41
X010713 Carbon	C33MR11BR12BC34B	0.83	2.528	6.53	6.27
	C33NC34C	0.67	2.999	4.69	70.2
	C33OC34D	1.25	2.969	4.41	123.9
UP6040 Resin	C33LR11AR12AC34AR12C	0.39		6.81	7.48
	C33MR11BR12BC34BR12D	0.48		7.38	9.86
	C33OC34DR12E	0.49		6.84	6.14

3.3.3 Production of Drinking Water using a Composition of Purification Train

The final water treatment train resulted in no regulated contaminants found in concentrations exceeding drinking water standards, but not all of the organic content of the water has been identified. Based on the previous water purification results a purification train was designed that consisted of two different granular activated carbons, a coal based activated carbon and Westvaco's low phosphorus wood based activated carbon with two different ion-exchange resin beds. The following beds were tested in the laboratory. Coal based granular activated carbon (GAC) from the Calgon Corporation. The condensate was run through the column at a flow rate of 32 ml/min. The condensate was a combination of condensates produced in runs W103-W115 with a TOC content of 58.6 ppm. After 0.7 gallons, the TOC was reduced to

8.1 ppm. The TOC remained between 7 –8 ppm up to 9.4 gallons. At 10.8 gallons, the TOC increased to 9.9 ppm. After another 1.4 gallons, the TOC had dropped to 5.3 ppm, and remained low for the rest of the treatment. The specialty wood based activated carbon was then used to treat the condensate after the water was purified by the coal based activated carbon. In some cases it was also used after the water had been filtered through the ion exchange resin. When this carbon was used after the Calgon carbon, it reduced the TOC down to 3.0 mg/L after 1.3 gallons. When used after a combination of the coal based GAC and both ion exchange resins (discussed later) the TOC was reduced from 3.2 to 1.5 mg/L after 0.5 gallons and 2.4 mg/L after 0.8 gallons.

An ion exchange resin from Sybron Chemicals, Inc. was used that was specifically designed to remove nitrogen compounds. When used after the coal based GAC, this resin actually increased the TOC from 5.3 mg/L to 7.4 mg/L after only 1.3 gallons. But when used after both activated carbon beds, it had no affect on the TOC (the beginning TOC was 3.0 mg/L and the ending TOC was 2.8 mg/L). An ion exchange resin from Rohm & Haas was then used after the carbons (with or without the previous ion exchange resin) whichremoved the remaining contaminants from the condensate. When this was used after the previous ion exchange resin, it reduced the TOC to 3.2 mg/L after 1.1 gallons. When it was used after the previous combinations of GAC it dropped the TOC from 3.0 mg/L to less than the detection limit of 0.5 mg/L (estimated to be 0.1 mg/L by the instrument). When this ion exchange resin was used again after the combination of GAC beds and the previous ion exchange resin followed again by the wood based GAC it reduced the TOC to 0.6 mg/L. After the combination of GAC beds and the previous ion exchange resin, the TOC was reduced to less than the detection limit of 0.5 mg/L (estimated to be 0.3 mg/L by the instrument).

Two samples were produced of high enough purity to be of drinking water quality according to the Army's tri-service long term water consumption quality standards. The best results were achieved by using a combination of the two carbon beds and the Rohm & Haas ion exchange resin column, labeled C33OC34DR12E (C33E) in Table 3. This sample had a TOC of only 0.1 ppm, a pH of 6.8 and conductivity of only 6.1**.** The other sample was purified through both carbon beds and both resin beds, and had a TOC of 0.3ppm (C33C). It was likely that the second resin bed gave off a small amount of TOC to the water to increase the TOC slightly to 0.3 ppm. The pH of the water was close to neutral at 6.8 and the conductivity was very low, 7.5 µS/cm.

The highest purity sample C33E was submitted to Chemir laboratories as well as EnviroData Group, LLC for inorganic and trace organics analysis to identify the nature of the 0.1 ppm of organic compounds left in the water. Envirodata group, LLC identified two organic compounds in the water: 4-Methyl-2-Pentanone (MIBK) at 17 µg/L (ppb) and toluene at 0.8 ppb. Chemir also identified traces of toluene as well as 2-ethyl-1 hexanol and small amounts of a polymer, all adding up to less than 0.1 ppm. Chemir and EDG conducted metals analysis on both samples as well. EDG only analyzed for the 26 metals regulated in drinking water while Chemir analyzed for all possible metals. All metals present were below regulated levels. Sodium was found at 2 ppm and Lithium at 1.2 ppb. Other metals were present in the <1 ppb range like Scandium 0.5 ppb, Molybdenum 0.13 ppb and Niobium 0.01 ppb, Aluminum 0.04 ppb and Ca < 0.01 ppb. The excellent results were due to introduction of the low phosphorus wood based activated carbon into the treatment train.

4 Summary & Conclusions

The primary goal of this work was to develop a fully integrated and automated prototype system for the collection, purification and storage of potable water from the exhaust gases of military land vehicles. A thin foil stainless steel thin channel counter current heat exchanger that could endure the flow, pressure drop, and corrosive environment of exhaust gases was developed that was less than half the size of the most advanced commercially available units. This has resulted in a current prototype that produces ½ gallon of water per gallon of diesel consumed that could eventually be mounted in a HMMWV wheel arch.

The water purification was performed using a treatment train consisting of a glass fiber filter, activated carbon and ion exchange resin. The water purification canister design was challenging since the water contains a mixture of organic and inorganic compounds and is very acidic. A small amount of drinking water was produced that meet EPA and military drinking water standards for long-term consumption with a total organic carbon (TOC) of only 0.1 ppm and metal concentration below detectable limits.