

AN IMPROVED CO₂ COOLING SYSTEM FOR THE UP-ARMORED HMMWV

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ABSTRACT

The U.S. Army has conducted a second generation design, fabrication, and test of a transcritical carbon dioxide cooling system on the M1114 Up-Armored High Mobility Multi-Purpose Wheeled Vehicle (HMMWV). The HMMWV cooling system is designed to cool military personnel and electronics equipment in hot ambient climates with rated conditions of 51.7°C outdoor ambient temperature. Carbon dioxide was selected as an alternate refrigerant because of its high potential for reduced logistics burden, cool-down performance, space and weight reductions, and environmental responsibility. During 2005-6, the U.S. Army, in collaboration with Modine and the University of Illinois, has conducted breadboard testing, full-scale prototype fabrication, instrumented laboratory tests, and proving ground operational testing. This paper summarizes those development and testing results.

1. INTRODUCTION

The U.S. Army is interested in the development of advanced heating and cooling products for battlefield cooling of tactical electronics systems and personnel. These cooling applications have become increasingly critical as the Army continues to operate in hot desert regions and adds armoring to its fleet of combat support vehicles, which necessitates the use of air conditioning in operator spaces. Transcritical carbon dioxide offers high performance cooling in smaller packages, with reduced logistics support requirements and greater environmental stewardship than prior technology.

The Army maintains a fleet of High Mobility Multi-Purpose Wheeled Vehicles (HMMWVs) of varying designs for use in combat support missions. (Figure 1.) HMMWVs were not originally designed or produced with air-conditioning systems of



Figure 1. Original M1114 HMMWV

Figure 2. Original R-134a Components

any type. In the mid-1990's the first armored HMMWVs (the M1114 designation) were produced as an after-market modification as armor was being added. Engine belt-driven compressors were supplied with the new vehicles, and the remainder of the cooling system was added by the armoring contractor. Insulated elastomeric refrigerant lines were fitted to the compressor, dual evaporators and air duct assemblies were added into the operating cabin and a remote condenser assembly was fitted to a rear fender area. (Figure 2.) The system utilized R-134a hydrofluorocarbon (HFC) refrigerant. The original design was expected to yield a pull-down of approximately 11°C at specified conditions, however, operational experience indicated difficulties in meeting this requirement in hot climates. In addition, armored HMMWVs met or often exceeded their maximum design weight limits, and the bulky copper-tube plate-fin heat exchangers added both undesirable weight and took up valuable interior compartment space.

2. FIRST GENERATION CO₂ STSTEM

Based on the early success of the Army laboratory in developing first generation Environmental Control Units (Manzione and Calkins, 2001) using CO₂ refrigerant, the Army Project Manager for Light Tactical Vehicles (PM-LTV) in the summer of 2003 became interested in exploring the feasibility of CO₂ cooling in the armored HMMWV. (Figure 3.) The initial objectives were to achieve the maximum capacity possible without exceeding the existing R-134a weight and space allocations. Furthermore, PM-LTV stipulated that the CO₂ system be physically configured to fit within the existing R-134a ductwork and heat exchanger packaging. (Figure 4.) The design team began by conducting several iterations of laboratory breadboards, varying high-side system pressures and system charge, compressor mass flow, number and location of internal heat exchangers, number and location of expansion devices, and general refrigerant routing. The final breadboard results indicated that the CO₂ system could yield a higher capacity



Figure 3. CO₂ M1114 HMMWV

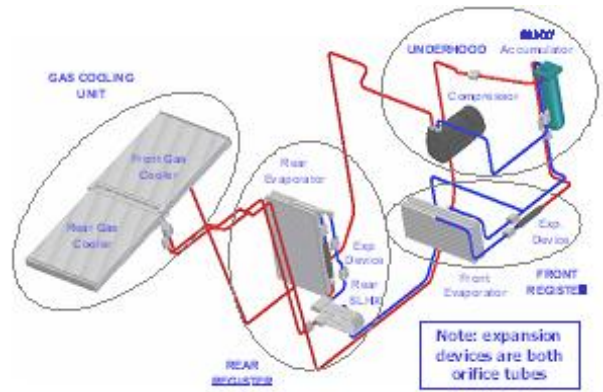


Figure 4. CO₂ System Schematic

(up to 57% higher) system, with COP improved by up to 18%. The physical CO₂ system was 8% lighter in weight than the baseline R-134a system, and with 30% smaller heat exchanger volume (Memory, et. al, 2005).

Following successful 2004 system tests at the SAE Alternate Refrigerant System Symposium and Death Valley National Park, PM-LTV directed that a 2nd generation CO₂ system be developed, this time with fewer physical constraints. While the compressor location would remain basically unchanged, the design team was free to install a larger displacement CO₂ compressor, new refrigerant line sets, and to rework the internal cabin evaporator and ducting arrangement. Although the CO₂ system had no defined efficiency target and program managers emphasized maximum possible capacity, the design team returned to the breadboard to first identify what might be possible.

3. SECOND GENERATION CO₂ SYSTEM

By the time the Army team began designing the 2nd generation CO₂ system, more insight into HMMWV operations was known. One was the frequent and repeated need to accomplish “initial pulldown” from a very hot cabin condition, while the crew members were underway. The performance of the cooling system was paramount in the first minutes of operation. A second was the common scenario of operating at idle with frequent opening of doors or with the center top hatch remaining open. The design team considered the benefits of cooling the occupants rather than cooling the entire HMMWV cabin, and elected to try and direct the cold air flow as close as possible to the HMMWV crewmember locations. Computational Fluid Dynamics (CFD) showed that this could be possible with overhead ducts running the length of the cabin interior, with rotatable discharge nozzles similar to commercial jet aircraft. Another goal was to eliminate the front evaporator assembly, which interfered greatly with front passenger leg room. A dual rear-evaporator scheme was devised, with transitional ductwork to the overhead nozzles. (Figure 5.)

High speed, higher velocity centrifugal fan assemblies were identified for installation into the ductwork. Under the hood, a 40 cc compressor was installed in the same location as before, and new refrigerant lines were added. (Figure 6.)



Figure 5. Rear Evaporator and Overhead Duct

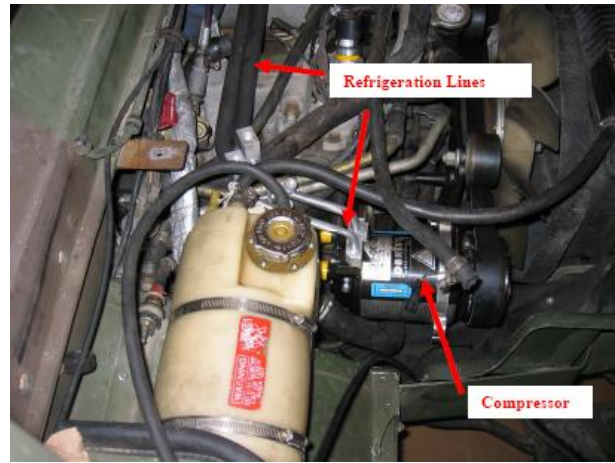


Figure 6. Compressor and Lines

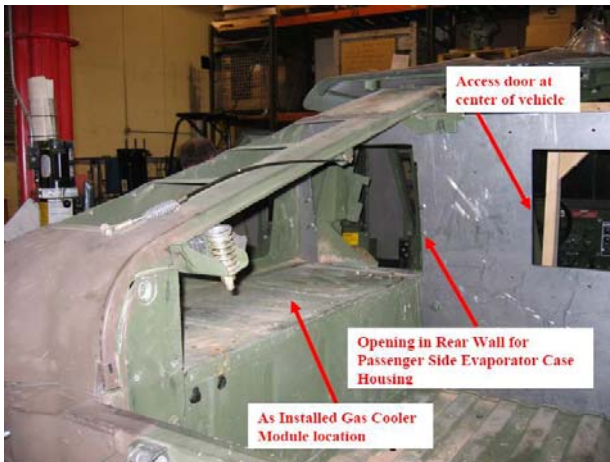


Figure 7. Gas Cooler Compartment

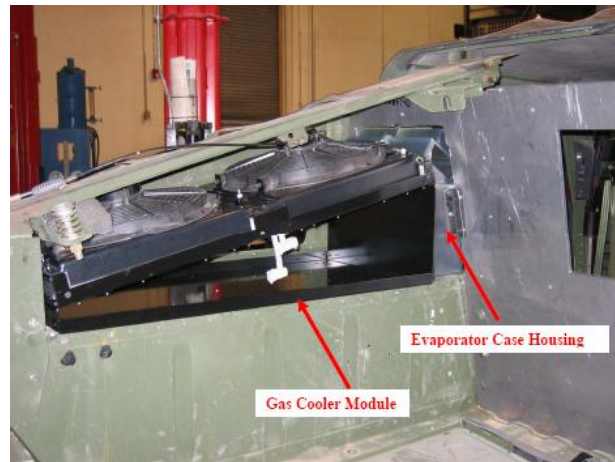


Figure 8. Gas Cooler & Fan Assemblies

In the rear of the HMMWV, the two evaporator case housings were located partway through the rear bulkhead, in closer proximity to the gas cooler. The SLHX/accumulator assembly was removed from under the hood to the gas cooler compartment in the rear of the vehicle. The arrangement is shown in Figure 7. Figure 8 shows the gas cooler installed in its compartment. For the new arrangement, refrigerant flow was split directly upstream of the gas coolers and combined immediately after. Overall, the improvement of heat exchanger core volume over the original R-134a system was 46% for the gas cooler and 72% for the evaporators.

The laboratory breadboard of the second generation system was then set up to match the arrangement in the HMMWV. Figure 9 shows the breadboard schematic. A matrix of 15 separate test conditions was determined, first varying the ambient gas cooler air temperature for 5 cases: 64°C (147°F); 58°C (136°F); 49°C (120°F); 43°C (109°F); and 35°C (95°F), and then for each ambient condition varying the engine speed in three increments to simulate vehicle speeds of 0 km/hr (0 MPH), 32.2 km/hr (20 MPH), and 64.4 km/hr, (40 MPH). The resulting test matrix is shown in Figure 10.

After breadboard data was taken, a plot of Cooling Capacity was generated and is shown in Figure 11. The maximum capacity of the CO₂ system of approximately 9 kW was

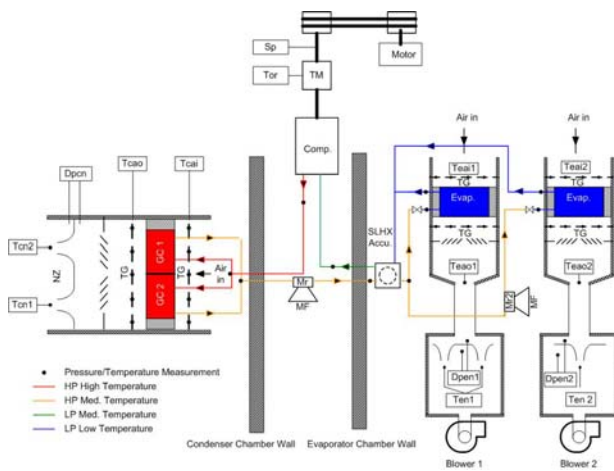


Figure 9. Breadboard Schematic

HMMWV R744 Phase II Breadboard Test Matrix												
Name	Vehicle Speed	Engine	Gas cooler				Evaporator (left and right)					
	MPH	RPM	°C	°F	m ² /s	cfm	°C	°F	%	Tdpei	m ² /s	cfm
I64-49-0.1	0	716	64	147	0.8	1700	49	120	20	20.0	0.08	169
L64-49-0.1	20	1371	64	147	0.9	1900	49	120	20	20.0	0.08	169
H64-49-0.1	40	2133	64	147	0.99	2100	49	120	20	20.0	0.08	169
I49-49-0.1	0	716	49	120	0.8	1700	49	120	20	20.0	0.08	169
L49-49-0.1	20	1371	49	120	0.9	1900	49	120	20	20.0	0.08	169
H49-49-0.1	40	2133	49	120	0.99	2100	49	120	20	20.0	0.08	169
I58-43-0.1	0	716	58	136	0.8	1700	43	109	30	21.7	0.08	169
L58-43-0.1	20	1371	58	136	0.9	1900	43	109	30	21.7	0.08	169
H58-43-0.1	40	2133	58	136	0.99	2100	43	109	30	21.7	0.08	169
I43-43-0.1	0	716	43	109	0.8	1700	43	109	30	21.7	0.08	169
L43-43-0.1	20	1371	43	109	0.9	1900	43	109	30	21.7	0.08	169
H43-43-0.1	40	2133	43	109	0.99	2100	43	109	30	21.7	0.08	169
I35-35-0.1	0	716	35	95	0.8	1700	35	95	40	19.4	0.08	169
L35-35-0.1	20	1371	35	95	0.9	1900	35	95	40	19.4	0.08	169
H35-35-0.1	40	2133	35	95	0.99	2100	35	95	40	19.4	0.08	169

Figure 10. Breadboard Test Matrix

achieved at several test conditions, and it was seen that the capacity of the CO₂ system exceeded the capacity of the original R-134a system at all 10 underway (non-idle) conditions. At engine idle, the CO₂ system performed equally to the R-134a system at lower ambients, and the R-134a system performed better at the higher ambients.

Next, the COP of the breadboard was plotted, and the results are shown in Figure 12. The COP of the CO₂ system was higher than the baseline R-134a at lower ambients while underway, but not at idle. At higher ambients, the R-134a system achieved higher COP. But since both engine RPM and airflow were lower for the 2nd generation CO₂ system than the 1st, it was decided as a final test to equalize the air flow rates. After increasing the air flow rates from 0.8 m/s to 0.99 m/s, it was seen that the 2nd generation CO₂ system provided the same cooling capacity and COP as the 1st generation system.

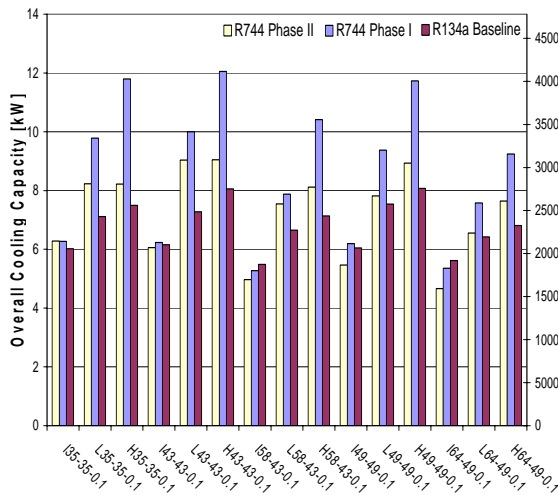


Figure 11. Cooling Capacity Comparison

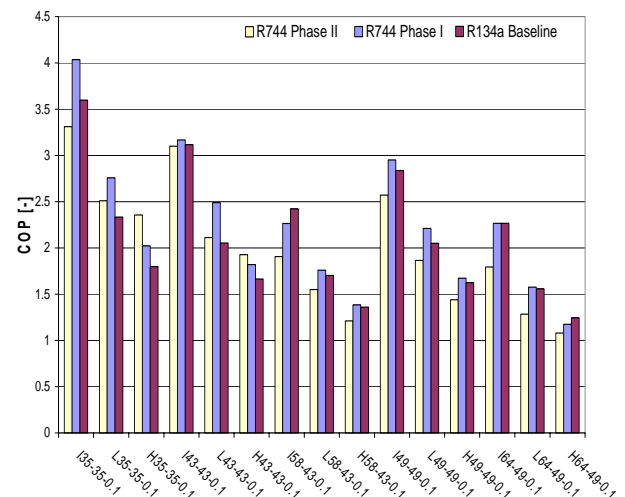


Figure 12. COP Comparison

4. WIND TUNNEL TESTING

The HMMWV was instrumented in the wind tunnel (Figure 13) and tested to the following conditions: 43.3°C (110°F) / 30% RH, and 48.9°C (120°F) / 20% RH. The road speed / engine speeds were matched to that of the 1st generation system: 1371 RPM, 2133 RPM, and 2971 RPM for 0 km/hr (0 MPH), 32.2 km/hr (20 MPH), 64.4 km/hr, (40 MPH), and 96.6 km/hr (60 MPH) respectively. At the rating condition of 48.9°C (120°F), the average interior temperatures are plotted vs. time in Figure 14. After 30 minutes of operation, at 32.2 km/hr (20 MPH), the CO₂ system had achieved an average interior temperature of 32.2°C (90°F), as compared to the baseline R-134a system which had achieved 40.6°C (105°F). Unlike passenger automobiles, the HMMWV at increasing engine speeds is subject to increasingly severe heat ingress from the engine. After 30 minutes of operation at 64.4 km/hr (40 MPH), the CO₂ system maintained an average interior temperature of 34.4°C (94°F), as compared to the baseline R-134a system which had maintained 41.7°C (107°F). At the 96.6 km/hr (60 MPH) condition, the CO₂ system was able to maintain an average interior temperature of 37.8°C (100°F), while at the same condition the baseline R-134a system was able to maintain 44.4°C (112°F).



Figure 13. HMMWV in Wind Tunnel

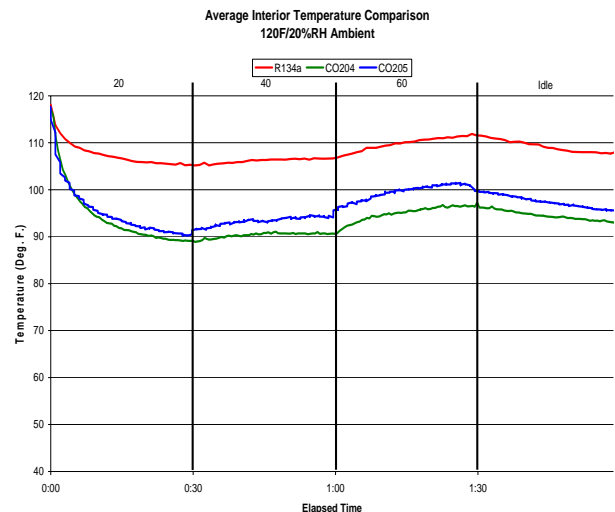


Figure 14. Average interior temperatures at varying engine speeds.

5. DEATH VALLEY FIELD TESTING

Following the completion of wind tunnel tests, the 2nd generation CO₂ HMMWV was taken to Death Valley National Park in the 3rd week of August 2005 in an attempt to obtain the hottest possible outdoor conditions in North America. A series of underway tests were performed over a three day period to simulate a variety of field operations, including idling, city stop/start driving, highway driving, and sustained mountain climbs of up to 15 km at 10% grade. One of the idle pull-down tests was conducted at “Badwater”, which at 86 m (282 ft) below sea level is the lowest point in North America. (Figure 15.) On the cloudless afternoon of 23 Aug 2006, the ambient temperature at



Figure 15. HMMWV at Badwater, Death Valley National Park

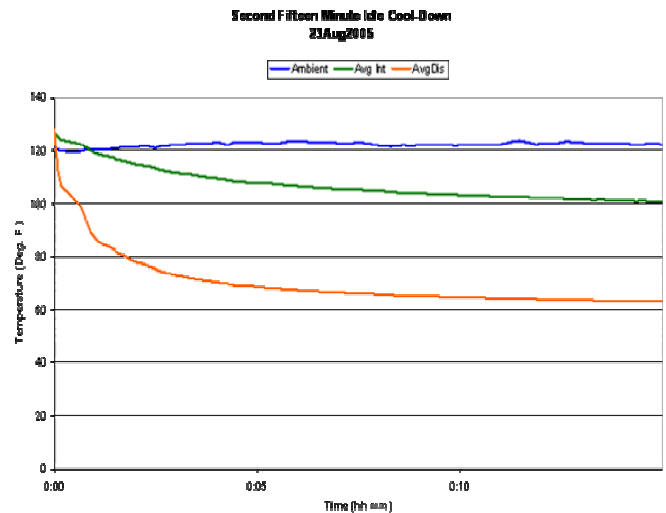


Figure 16. Fifteen minute idle pull down test - average interior temperatures

Badwater reached 120°F. An idle pulldown test was performed. The HMMWV was positioned facing into the sun and allowed to heat soak for a period of one hour. Then it was started and operated at idle for a fifteen minute period while temperatures were recorded. Figure 16 displays the cooldown profile. After 5 minutes, the average discharge temperature of the CO₂ system was 20.6°C (69°F) and the average interior temperature was cooled to 42.2°C (108°F). After 10 minutes, the average discharge temperature of the CO₂ system was 17.8°C (64°F) and the average interior temperature was cooled to 40°C (104°F). After 15 minutes, the average discharge temperature of the CO₂ system was 16.7°C (62°F) and the average interior temperature was cooled to 38.3°C (101°F).

6. CONCLUSIONS / FOLLOW UP ACTIONS

Two generations of CO₂ cooling systems installed on an M1114 Up-Armored HMMWV have demonstrated the technical feasibility of the new technology, and the ability to maximize capacity at smaller installed volumes and lighter weight. Quicker and deeper temperature pulldown profiles were measured in an instrumented laboratory and in extreme temperature field tests. Directional cooling through high velocity nozzles has proven to be an effective alternative to lower volume duct flow. The used of breadboard laboratory modelling was instrumental in determining many system factors such as refrigerant charge and sizing of components.

Without sustained mass production of CO₂ systems in the automotive sector, it remains economically difficult for low-volume users like the military to adopt CO₂ immediately as a retrofit to fielded equipment such as the M1114 HMMWV. However, insertion of the new technology into developmental prototypes for the future family of tactical military vehicles appears to be the more viable option, and the Army team intends to explore these possibilities next.

7. NOMENCLATURE

<i>CFD</i>	Computational Fluid Dynamics
<i>COP</i>	Coefficient of Performance
<i>HFC</i>	Hydrofluorocarbon
<i>HMMWV</i>	High Mobility Multi-Purpose Wheeled Vehicle

<i>PM-LTV</i>	Project Manager, Light Tactical Vehicles
<i>RH</i>	Relative Humidity
<i>SLHX</i>	Suction Line Heat Exchanger

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