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Energy Research and Development Division

FINAL PROJECT REPORT

Carbon Dioxide-Based Cleaning of Military Textiles

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Carbon Dioxide-Based Cleaning of Military Textiles is the final report for the project conducted by TERSUS Solutions. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/).

ABSTRACT

TERSUS Solutions developed and demonstrated a liquid carbon dioxide (CO_2)-based cleaning solution for cleaning military textiles and garments. Port Hueneme Naval Base served as the demonstration location for this project. During this project TERSUS Solutions, and its partners, designed, built, installed, validated and operated a CO_2- based military garment cleaning machine. Adapting TERSUS Solutions' existing textile and garment cleaning equipment to operate in a military setting overcame two main challenges: scaling of the equipment to handle increased volume and a process to validate cleaning at military standards.

TERSUS Solutions demonstrated 76 percent higher operational efficiency (for example, higher throughput) and 15 percent utility savings compared to traditional water-based cleaning methods. Additionally, TERSUS CO_2-based cleaning system showed savings of 117.5 gallons of water per every 150 pounds of laundry.

This project demonstrated that widespread adoption of TERSUS Solutions cleaning system is environmentally preferable by substantially reducing the water, energy and natural gas consumption of military textile cleaning. Beyond the Department of the Navy, these solutions can service multiple military and government institutions, amplifying their environmental and financial impact.

Keywords: Carbon dioxide (CO_2), carbon dioxide-based cleaning, textiles, garments, validation, utility consumption

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Cleaning and processing textiles and garments, from uniforms to technical garment such as ballistic vests to oily waste rags, is difficult, costly, requires extensive use of chemicals, energy and water. Some technical garments, such as ballistic vests, cannot effectively be cleaned in water without potential damage, reducing the life of the vest. Additionally, the cleaning process for military textiles and garments is difficult, costly, and energy (natural gas/electrical) and water intensive. The Navy also emphasized the need to be able to clean technical garments on-site, rather than contracting outside vendors.

This project explored using carbon dioxide (CO_2) as a cleaning solution since it is a naturally occurring and abundant gas that has excellent solvency properties when it becomes a liquid or a supercritical fluid. CO_2 can exist in solid (dry ice), gaseous, liquid or supercritical states depending on temperature and pressure conditions.

In addition to cleaning well, CO_2 leaves no secondary waste and is the same gas that is used, for example, in beverage fizz at every local restaurant with a soda dispenser. No new CO_2 is generated or added to the atmosphere by the CO_2-based textile cleaning equipment. In fact, the CO_2 used during operation is waste or byproduct carbon dioxide generated by industrial facilities. It is non-hazardous, non-mutagenic, non-flammable, non-toxic, and non-ozone depleting. Due to its excellent cleaning properties and environmental and health aspects, CO_2 is used across multiple industries including pharmaceuticals, food manufacturing, de-contamination and sterilization.

Project Purpose and Approach

This project focused on using a liquid CO_2-based cleaning solution for washing military grade garments and textiles such as Kevlar® vests or fire-retardant uniforms. Previously, such garments and textiles either had no cleaning option or only a water-based cleaning process. TERSUS Solutions wanted to verify that a liquid CO_2-based cleaning process preserved the technical functionality and was more efficient than the current cleaning systems.

The innovative TERSUS AA-75 machine, installed at the Port Hueneme Naval Base in Ventura County, was completely redesigned for size and capacity. While the machine was running, data was recorded, and the cycle was observed. Parameters were modified and new code blocks/parameters were introduced to the machine. Of these, pressure, temperature, time, pump and basket speed were all adjusted to achieve the highest possible cleaning efficiency.

The researchers selected garments either not currently laundered or are difficult to launder due to the technical aspects of the garments such as fire repellency, thermal characteristics, and durability. Liquid CO_2 also has the ability to decontaminate while maintaining fire repellent items such as fire turnout gear and other fire protective equipment. CO_2 can pass through any density of the fabric to clean while a water system requires chemicals for the water to pass through and heat to remove that water. Garments with numerous layers and densities, such as Kevlar® vests or fire-retardant uniforms, can be cleaned easily in CO_2 without chemicals or extended drying steps.

Cleaning without chemicals and heat is crucial for fire protective gear. Any chemicals left after cleaning exposes the fire fighters to a fire risk from the chemical being potentially flammable.

Heat and tumbling of the dryer can cause damage and premature wear of the material. After a fire, the garments are contaminated with polyaromatic hydrocarbons and volatile organic compounds from the burning materials and smoke in the buildings. The TERSUS AA-75 Liquid CO_2 process is especially suited to decontaminate this type of gear, keeping the fire fighters safe and healthy from not breathing these contaminates when wearing or shelving these garments.

Project Results

The Tersus equipment excelled at cleaning and decontaminating difficult and delicate military textiles and technical garments using a waterless cleaning process. TERSUS Solutions demonstrated improved operational efficiency (76 percent higher efficiency) and 15 percent utility savings compared to traditional water-based cleaning methods. Additionally, TERSUS CO_2-based cleaning system showed savings of 117.5 gallons of water per every 150 pounds of laundry. Several barriers were overcome during this project including establishing cleanliness standards, testing methods, and modifying processes to reach the rigorous military standards.

Benefits to California

The innovative TERSUS AA-75 machine provided a cleaning process with low environmental impact (reducing energy consumption and eliminating water) and low cost (operational and capital investment). Each Tersus machine can replace two large commercial sized washers and dryers or three standard commercial sized washers and dryers. Water savings average approximately 16.7 gallons per wash cycle, totaling approximately 100 gallons per day per machine replacing six water wash cycles per day. From the energy standpoint, to match the throughput of a Tersus machine, one industrial washer and dryer would consume an extra 187 kilowatt hours of electricity per day. These water and energy savings would scale as Tersus machines replaced water washers and dryers on naval bases across the country.

TERSUS Solutions confirmed the viability of cleaning and maintaining the ballistic properties of ballistic vests (modular tactical vests – MTV) without the use of water or chemicals. Unpleasant odors and oils from heavy use are removed to provide a clean and comfortable vest for the service personnel to wear. These items are rarely laundered, if ever, which presents challenges for comfort and overall satisfaction. A TERSUS machine installed in the requisition bases across the country could result in a drastic increase in overall satisfaction of the re-requisitioned garments when worn, especially for heavy use items such as the ballistic vests. Satisfaction throughout the entire handling process would increase because operators would not handle un-cleaned items. Additionally, requisition officers would see an increase in overall job satisfaction by not having to issue dirty garments to service personnel. While this may not be able to be quantified into a monetary number, job satisfaction and health can result in a more productive operation.

CHAPTER 1: Introduction

Purpose and Focus Area

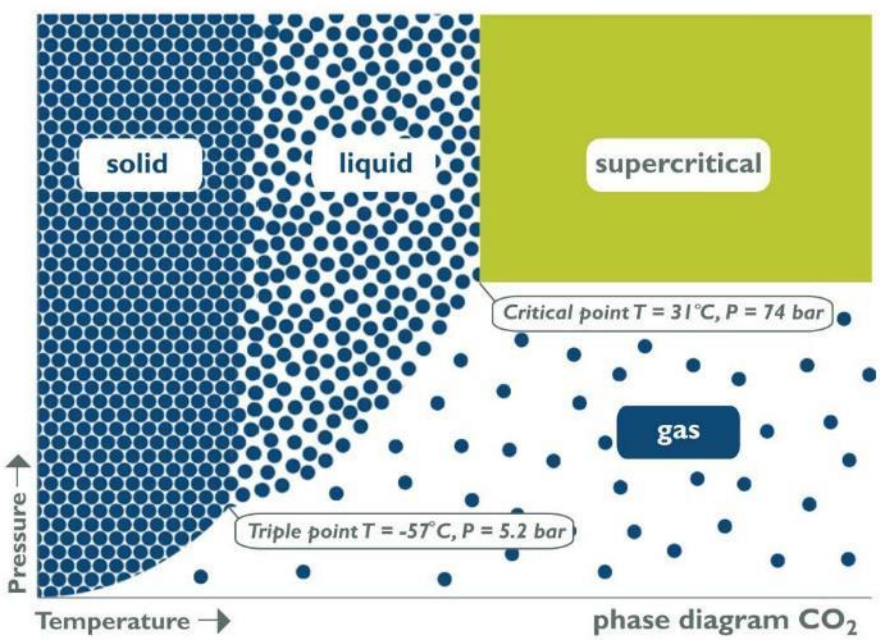
This project introduced liquid carbon dioxide (CO_2) textile cleaning into the military sector, which previously only used water as the cleaning solvent. Garments, such as ballistic vests, had no viable cleaning method due to potential reduction in quality standards and functionality. Implementing TERSUS Solutions' technology saves substantial energy, water and waste, and benefits public health and quality of life.

The military sector was targeted as large consumer of textiles and garments. Finding an efficient cleaning solution would be a great accomplishment. TERSUS Solutions embarked to prove cleaning military textiles and garments via liquid carbon dioxide would produce superior results.

Introduction to Carbon Dioxide

Carbon dioxide is a naturally occurring and abundant gas that has excellent solvency properties when it becomes a liquid or a supercritical fluid. In addition to cleaning well, CO_2 leaves no secondary waste. The CO_2 used is the same gas that is used, for example, in beverage fizz at every local restaurant with a soda dispenser. No new CO_2 is generated or added to the atmosphere by the CO_2-based textile cleaning equipment because the CO_2 used during operation is waste or byproduct carbon dioxide generated by industrial facilities. It is non-hazardous, non-mutagenic, non-flammable, non-toxic, and non-ozone depleting (Figure 1). Due to its excellent cleaning properties and environmental and health aspects, CO_2 is used across multiple industries including pharmaceuticals, food manufacturing, de-contamination and sterilization.

Figure 1: Carbon Dioxide Phase Diagram



Source: TERSUS Solutions

CO_2 can exist in solid (dry ice), gaseous, liquid, or supercritical states depending on the temperature and pressure conditions present. Solvency properties which are important for garment cleaning include:

- Low viscosity and surface tension, resulting in small pore penetration.
- High density, resulting in strong solvent properties.

Product Demand and Potential Impact

Water scarcity and depletion is a serious problem across the United States, particularly in the West. Traditional water-based laundering has been and continues to be one of the major water consumers. Water use also correlates with energy intensity. After water-based washing, garments must be dried to remove the remaining water, which requires energy. With water and energy sources dwindling, it's no surprise state and federal legislators have been encouraging utility conservation from the public and private businesses for some time.

The benefits of implementing CO_2 textile cleaning at military facilities throughout California are significant, including:

- Reducing energy demand.
- Preserving scarce water sources.
- Reducing textile cleaning related wastewater/sewage.

CHAPTER 2: Method

Technology Status

Carbon dioxide has been commercially used to clean garments – primarily consumer dry cleaning garments – since the early 2000's. TERSUS Solutions and partners have been developing new applications of CO_2-based textile cleaning since 2008. TERSUS Solutions maintains intellectual property and know-how in the cleaning of numerous garment types and industrial textiles. As shown in Figure 2, the Tersus Cleaning Solutions is a universal cleaning system for industrial laundry services, commercial and retail dry cleaners, uniform cleaning providers, uniform based institutions (for example hotels, casinos, corrections facilities, and military), as well as various niche processing applications (for example oil and gas industry, coating protected garments, and fire fighter turnout gear).

Figure 2: TERSUS AA-75

Source: TERSUS Solutions

The cleaning cycle of gaseous CO_2 is introduced into the cleaning chamber and pressurized into liquid form (about 700 psi and 60 °F). Garments go through a cleaning cycle, after which the chamber is de-pressurized, thereby returning the CO_2 to a gaseous form and leaving the garments dry and cool to the touch. Unlike conventional water-based cleaning, no heat is required to dry clothes which results in longer lasting fabrics and significantly faster cycle times. All the CO_2 is circulated through a filter to remove particulates, distilled (to remove impurities like body oils and other extraneous items) and returned to be reused. The only waste stream is the oils and additives that are extracted via distillation, which, depending on application, can be recycled for other uses, such as in bio-diesel blends.

Benefits of CO_2-based textile cleaning include:

- Environmentally sustainable – no chemicals, no water, and no hazardous secondary waste stream.
- No heat – garments last longer and retain their functionality/quality.
- Faster cycle time – for increased throughput.
- Single machine needed for both wash and dry.
- Reduced utility bills – due to reduced water, electricity, and natural gas use and no waste stream remediation.
- Streamlined operations – simplified workflow, shorter processing time, and less labor needed.
- Overall lower operation costs.

With this project TERSUS Solutions endeavored to develop a CO_2-based solution for the cleaning of military textiles and garments.

Military Cleaning

The Department of Navy used a third-party cleaner to process sleep systems, high end Goretex jackets, Goretex pants, and Level 7 jackets. These garments were not cleaned on the base but contracted out to an industrial laundry off-base. The on-base Navy warehouse oversaw the logistics of issuing and receiving the items from the troops. The sailors were responsible for cleaning their day to day garments and uniforms. The MTV and other ballistic vests were not cleaned at all, including by external vendors.

Challenges

The challenges of adapting TERSUS Solutions' textile cleaning equipment and know-how to service military laundry were two-fold:

- *Equipment:* The machined had to be scaled to be able to process 75 pounds of garments to achieve the throughput capacity required to switch from the current military laundry model and included design elements, such as filters and detergents, to account for the rigorous cleaning standards.
- *Process:* While carbon dioxide has a significant history being an effective cleaning and disinfection method, to operate as a service for military textiles, cleaning performance must be validated via a thorough process. TERSUS Solutions had to go through a process development cycle, to ensure cleaning standards are consistently met.

Goals and Objectives

The goals and objectives of the project were to:

- Develop and demonstrate the feasibility of CO_2-based cleaning of military textiles.
- Develop and demonstrate validated cleaning programs to address the various garment types and styles serviced in military laundry.
- Demonstrate operational efficiency and lower operational costs for end-users (such as military laundry service providers).
- Demonstrate utility use:
    - Reduce energy consumption
    - Eliminate water use
    - Eliminate waste water

CHAPTER 3: Activities

Project activities began June 2015 and continued through February 2018. The following is a summary of activities as determined by the project's scope of work.

Demonstration Partner

At the start of the project, the Department of the Navy was secured as the demonstration partner.

Design and Engineering

The TERSUS AA-75 machine designed for this project was completely redesigned to accommodate the expected volume of garments. This design effort was completed by the TERSUS Solutions Technical Team and the fabrication partner Compression Leasing Services located in Casper, Wyoming. TERSUS completed the engineering, process design and assembly of the equipment. Compression Leasing Services provided the space and tools for the fabrication and assembly. Compression Leasing Services also engineered the pressure vessels in accordance with ASME Section 8, Division 1 code. Since this machine was the first of its kind regrading size and capacity, many changes were made, including:

- Upsized the cleaning vessel to 33-inch ID, giving a total fluid capacity of about 700L.
- Increased wall thickness from 0.75 inch to over 1.375 inch.
- Upsized and redesigned the main door to be easier to operate and use.
- Upsized the distillation vessel to match the cleaning vessel and to hold the amount of fluid required to keep the machine running smoothly.
- Redesigned the double helix coil in the distillation vessel to work with not only steam but hot water or oil, oil being used in this case due to the lack of water infrastructure.
- Upsized storage vessels and added a second clean storage vessel to hold the correct amount of clean CO_2 required for use with a larger cleaning vessel.
- Redesigned skids for assembly ease and ability to support the extra weight of the vessels.
- Redesigned process flow to accommodate the extra storage tank, location of isolation valves for service and the addition of a radar level sensor to measure liquid level in the storage tanks.
- Redesigned basket and drive system to account for the extra weight the machine.
- Reprogramed machine and updated HMI to account for the extra volume and rate of pressure and level changes.

Fabrication and Assembly

Fabrication and assembly took place from September 2015 through October 2015 after the bill of materials was fully sourced and the various components arrived. Throughout the assembly period, the following items were completed:

- Vessels mounted to the skids.
- Heat exchangers set in place.
- Safety valve vent headers installed.
- Pumps and drive system assembled and installed.
- Process piping and sensor placement completed.
- Heating piping run to still and cleaning vessel heat exchanger.
- Chiller lines run to storage tank heat exchangers.
- Electrical wiring and terminations.
- Air lines run to pneumatic valves.
- Front panels fabricated (installation of these completed on site).

By October 2015, the machine was fully assembled and passed mechanical and functional testing protocols established by TERSUS Solutions. All fabrication and assembly activities were completed at the fabrication partner's facility, Compression Leasing Services in Casper, Wyoming. Figures 3-9 illustrate progress of the assembly process.

Early Stage Assembly (September 2015)

Figure 3: Cleaning Vessel Fabrication

Source: TERSUS Solutions

Figure 4: Cleaning Vessel Fabrication

Source: TERSUS Solutions

Figure 5: Cleaning Vessel Main Closure

Source: TERSUS Solutions Inc.

Mid-Stage Assembly (October 2015)

Figure 6: Skid 2 Assembly

Source: TERSUS Solutions Inc.

Figure 7: Skid 1 Assembly

Source: TERSUS Solutions Inc.

Final Stage Assembly (October 2015)

Figure 8: TERSUS AA-75 Final Assembly

Source: TERSUS Solutions Inc.

Figure 9: TERSUS AA-75 Machine Loading

Source: TERSUS Solutions

Installation and Commissioning

Pre-installation preparations took place at Naval Base from July through September 2015, which included installation of an onsite CO_2 tank and construction of three concrete pads to accommodate the following:

- The TERSUS AA-75 CO2 Textile Cleaning unit.

- The External CO2 storage tank and machine chiller.
- The electrical transformer.

In addition, an interior water drain below the boiler was fitted. 480 Volt, 3-phase high voltage power was brought into the space to power the TERSUS machine, boiler, and chiller. A trench was dug from the adjacent building to provide power to the new transformer. New electrical shutoffs were installed to the TERSUS AA-75, the oil heater used for distillation on the TERSUS machine, and the chiller unit outside. Lights and illuminated exit signs were installed to ensure that the space was safe in case of an emergency. Electrical outlets were installed behind the TERSUS AA-75 to allow for an air compressor and CO_2 monitor to be installed. Lastly, a water supply line was installed for the make-up water on the chiller.

The TERSUS AA-75 was shipped to the Naval Base in October 2015. Set-up, start-up and commissioning took place through November 2015 (Figure 10). The machine was brought into place and set in the established position as agreed upon in the categorical exclusion (Appendix A). The chiller, oil heater and air compressor were all set into their dedicated locations. Once the equipment was set, everything was bolted down and anchored to the floor for seismic protections.

Connections between the two TERSUS AA-75 skids were made, as well as connections to the supporting equipment. Approved licensed electrical contractors performed the final electrical hook ups to the TERSUS AA-75, the water chiller and the oil heater. The energy monitoring equipment was then installed into the main power panel to monitor the Tersus machine, oil heater and chiller, independently. Once the power had been run, the breaker panel was reassembled, and the power was turned on to all the pieces of equipment. Water lines were installed between the water chiller and the TERSUS machine as well as the make-up water line to the chiller.

For safety, the machine was manufactured with four vent lines. These vent lines, as shown in the machine layout drawings in the machine technical specifications (Appendix D), had to be run outside of the building in the case of an emergency event. The two large 3-inch vent headers (one per skid) were running outside and angled down, with grates on the ends to prevent build up in the lines. The purge, being a lower pressure set point, was run separate. Lastly, the main process vent was extended outside. To accommodate the vent lines, holes were drilled in the side of the steel building using a hole saw.

The last piece completed was installing a gate and fence that closed in the space and isolated the machine from the rest of the warehouse. The space had to be isolated to prevent TERSUS employees from entering the Navy warehouse space. A large gate was installed after reviewing the process flow of how garments would travel from the adjacent building and into the TERSUS space. The gate was large enough to allow large laundry carts to pass through and was locked using a specified Navy lock. The installation and commissioning of the machine satisfied the Phase 1 and Phase 2 requirements by the CATEX agreement (Figure 11) (Appendix A).

Figure 10: Receiving and Setting Machine

Installation Begins in Ventura County, October 2015

Source: TERSUS Solutions

Figure 11: TERSUS AA-75 Installation Complete

Installation Complete

Source: TERSUS Solutions

Operator training for the TERSUS AA-75 took place on the Naval base over three days. Day one included an overview of the machine and all major components. Descriptions for all the daily procedures were reviewed including start and end of day procedures, opening and closing the door and starting a cycle. The TERSUS technical team conducted a cycle demonstration to further explain the process steps to the operator.

Day 2 focused exclusively on machine safety. All safety features of the machine were covered and thoroughly explained to the operator. Safety measures are outlined in the TERSUS AA-75 safety manual (Appendix C). The CO_2 monitor was discussed at length as well as the procedure for when the CO_2 level rises. The safety features of the machine covered during the training included: the proximity sensors on the doors, all the sensors and associated safety features in connection to main PLC code, the safety valves and the sounds made in a vent incident. The operator also received training on the emergency shutdown procedure and the required actions during an emergency.

Day 3 focused on the operator becoming comfortable with running the machine. This was accomplished by running multiple cycles to allow the operator to learn the operations and procedures. Hands on experience is crucial to understanding the cycle and what noises can mean in terms of issues. Machine maintenance was covered, and the operator was shown how to change filters, remove sludge/waste out of the machine, replenish detergent and chemicals and other basic maintenance items for the machine. Major maintenance items were to be serviced by the TERSUS technical team and included: pump repair, drive line repair or any other major problems.

During the training period, process optimization of the machine continued. While the machine was running, data was recorded, and the cycle was observed. Parameters were modified and new code blocks/parameters were introduced to the machine. Of these, pressure, temperature, time, pump and basket speed were all adjusted to achieve the highest possible cleaning efficiency possible. The most important code steps added was the durable water repellency (DWR) block. These adjustments helped keep cycle times down while retaining cleaning abilities.

Operational Validation and Operations

To demonstrate that TERSUS Solutions cleaning system would retain or improve upon the quality of the current cleaning method, TERSUS Solutions set out to clean garments in standard water-based cleaning system to establish a baseline.

Garment Selection

Initially, a walk-through of the operations warehouse was conducted to determine the feasibility of potential items to clean. The first criteria were to find items that were not currently laundered or were very difficult to launder. This made the MTV vests and sleep systems ideal candidates. The second criteria were the technical aspects of the garments such as DWR application, fire repellant, thermal characteristics, and durability. DWR application and reactivation has been done successfully on workwear using the TERSUS liquid CO_2 process. Based on this, DWR was one of the areas chosen to test. Liquid CO_2 will also decontaminate and maintain fire repellent items such as fire turnout gear and other fire protective equipment. Due to the properties of CO_2 described, density of the fabric is not an issue for CO_2 to pass through and clean. A water system will require chemicals for the water to pass through and heat to remove that water. Garments like the ballistic panels and the carriers are examples of items that can be cleaned easily in CO_2 without chemicals or extended drying steps.

Fire gear, having many different layers and material densities, are another great example of a perfect item for CO_2 cleaning. Once again, cleaning without chemicals and heat is crucial for fire protective gear. Any chemicals left after cleaning exposes the fire fighters to a fire risk from the chemical being potentially flammable. Heat is needed to get the water out of the fire equipment and if not completely removed, can evaporate when in a fire and cause severe burns to the fire fighter. Further, heat and tumbling of the dryer can cause damage and premature wear of the material. After a fire, the garments are contaminated with polyaromatic hydrocarbons and volatile organic compounds from the burning materials and smoke in the buildings. The TERSUS AA-75 Liquid CO_2 process is especially suited to decontaminate this type of gear, keeping the fire fighters safe and healthy from not breathing these contaminates when wearing or shelving these garments.

Phase 1: Baseline Testing

Initially, TERSUS Solutions needed to assess how the current water cleaning system effected textiles and garments. TERSUS Solutions selected the component Sleep System, Goretex Jacket, Goretex Trousers and Poncho to be processed in the water cleaning system to establish a baseline for this demonstration. Baseline testing was conducted at a local laundromat (Town Square Coin Op Laundry) from May 10, 2016 to May 23, 2016 (Figures 12 and 13).

The process for all items included the following steps:

- Inspection and tagging of the items for identification purposes through the process.
- Photographing of the items prior to processing.
- Dividing items of same category (Sleep System, Goretex Jacket, Goretex Trousers, Poncho) into their designated subgroups (10, 20, 30).

These items were then washed according to corresponding group. A cycle is defined as the combination of the wash and the dryer cycle. The 10-subgroup was washed 10 full cycles, the 20 subgroup was washed 20 full cycles, and the 30 subgroup was washed 30 full cycles. All items were inspected after every cycle and any noticeable defects or changes were noted. After the items completed the required washes, the items were sent to HP White to be tested.

Water washed items included sleeping system, Goretex jacket, Goretex trousers, and poncho.

Figure 12: Town Square Coin Op Laundry, November 2015

Source: TERSUS Solutions Inc.

Figure 13: Town Square Coin Op Laundry, November 2015

Source: TERSUS Solutions Inc.

Phase II: CO_2 Testing

After the water washes were completed, TERSUS Solutions conducted washes using the liquid CO_2 process in the TERSUS AA-75. The same garments, and additional available garments were processed using the same benchmarks for cycle numbers (10x, 20x, 30x).

CHAPTER 4: Results

Carbon Dioxide Versus Water Textile Laundering Analysis and Comparison

The energy used by the TERSUS AA-75 machine was monitored while laundry testing was being completed. Once the data was collected and analyzed, a period was selected to show the overall energy use of the system. The testing took place over several months, as the period selected needed to have energy data as well as an adequate number of cycles. The energy monitor data selected for analysis was January 9, 2017 through February 8, 2017. During this range the machine ran consistently and allowed sufficient data by avoiding artificially low numbers of cycles being run due to the machine being out of cycle for extended periods of time. The results give a high-level overview of the numbers. The raw data for that time range can be seen in Appendix H.

The energy data collection was split into three different components: The machine itself (energy drawing items are the pump motor, basket motor and controls), the chiller (circulation pump and main refrigeration circuit) and oil heater (circulation pump and heating elements). The data loggers accounted for the voltage, three phase amp use, and power factors when calculating the total kilowatt per hour use. Figures 14 and 15 show the energy monitoring setup that was used during the demonstration.

Figure 14: Phase Energy Monitors

Source: TERSUS Solutions Inc.

Figure 15: Energy Monitoring Equipment

Source: TERSUS Solutions Inc.

For the time period selected, the energy values were:

1. Machine: 449.35 kilowatt-hours (kWh)
2. Chiller: 693.97 kWh
3. Oil Heater: 1482.42 kWh

These values were calculated by taking the ending continuous power counter read from the master control box and subtracting the beginning number. The data logger collected readings every 15 minutes on each leg of all the devices.

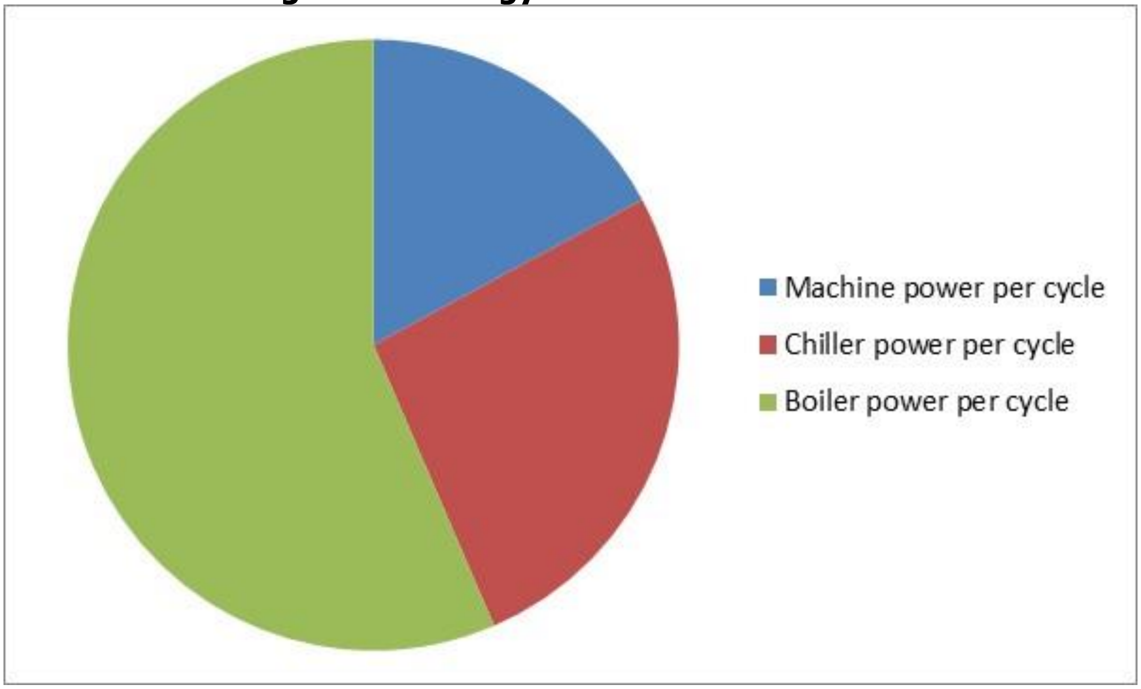
To calculate the number of cycles during the selected time range required highlighting the power usage (in the raw data) anywhere that the instantaneous current was higher than 0.4 amps for the machine, 0.14 amps for the chiller and 0.01 amps for the oil heater. A cycle count of 66 was calculated, which corresponds with the tests run during the energy testing period. The low-end numbers (0.4, 0.14 and 0.01) indicate when the equipment is out of cycle.

During this analysis of the TERSUS Equipment, the average power required to run a cycle are:

1. The TERSUS machine averaged 6.8 kWh per cycle.
2. The chiller averaged 10.5 kWh per cycle.
3. The oil heater averaged 22.5 kWh per cycle.

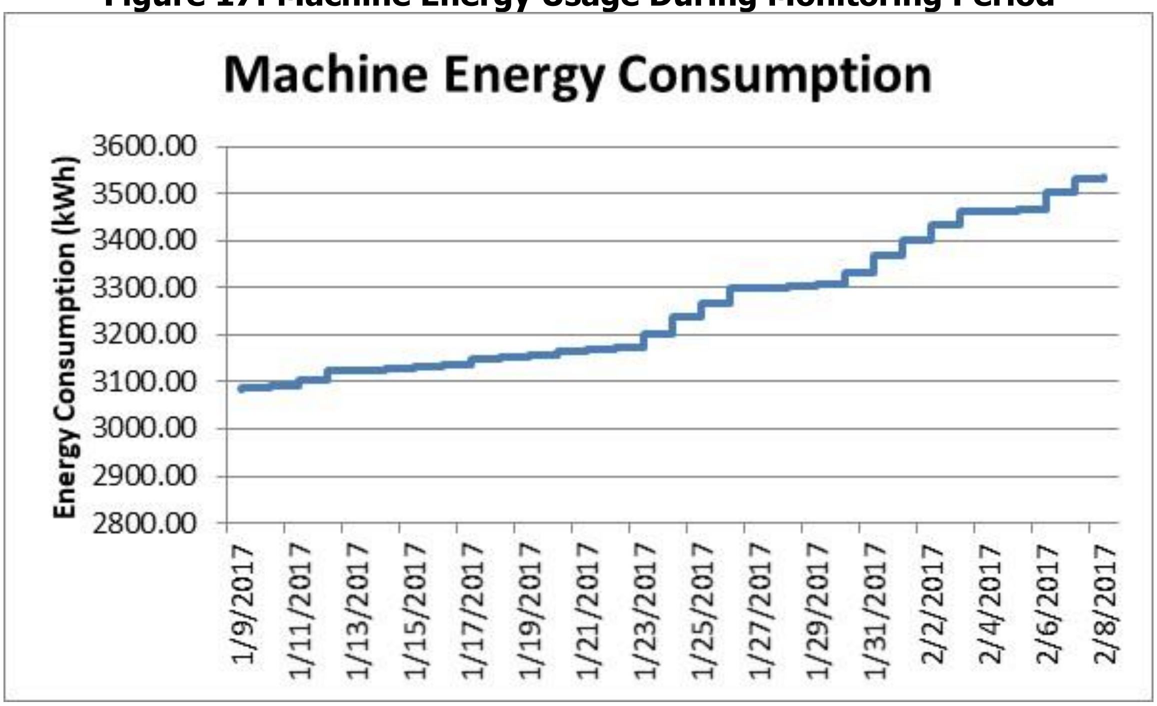
This gives a total energy usage average for the entire system of 39.8 kWh per cycle for 75 pounds (lbs) of textiles. Figure 16 shows a breakdown of the power used per piece of equipment.

Figure 16: Energy Of the TERSUS AA-75



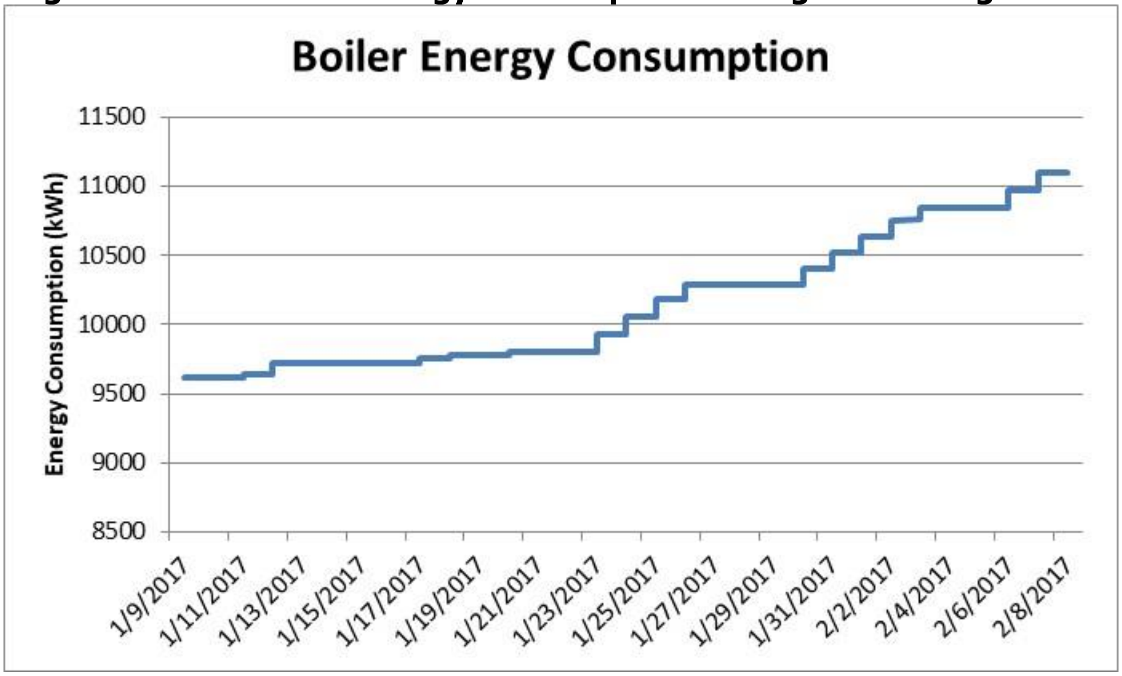
Source: TERSUS Solutions Inc.

Figure 17: Machine Energy Usage During Monitoring Period



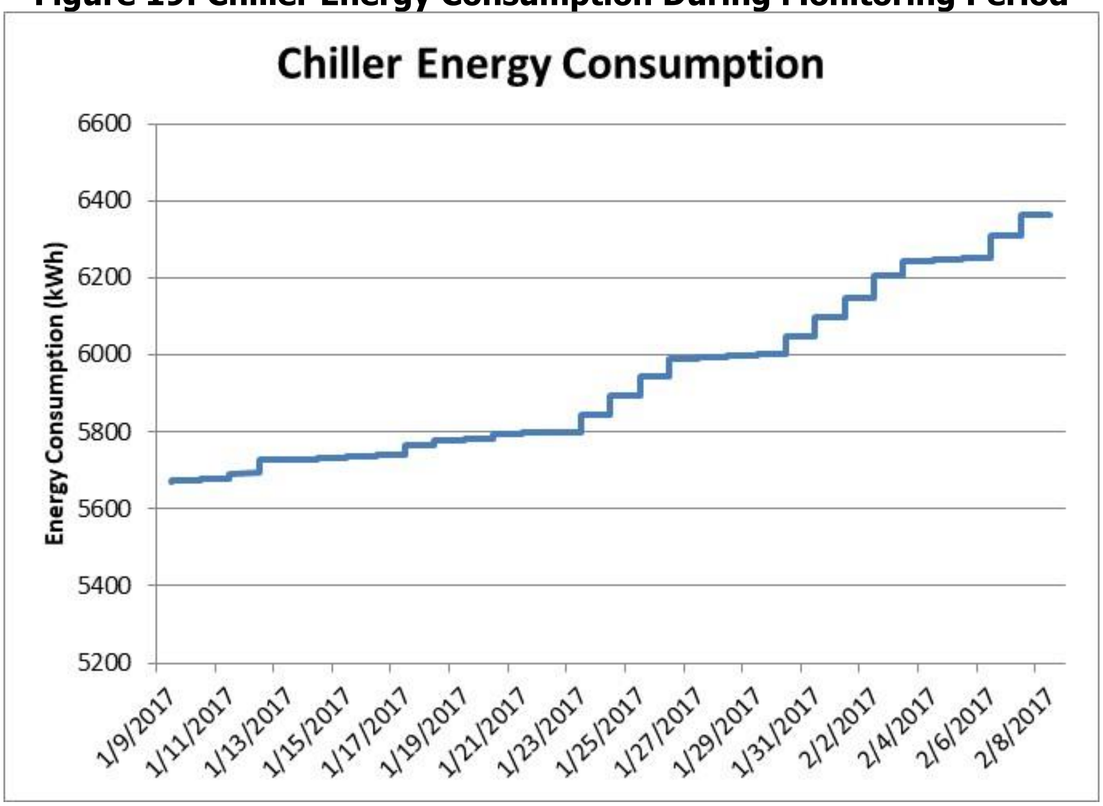
Source: TERSUS Solutions Inc.

Figure 18: Oil Heater Energy Consumption During Monitoring Period



Source: TERSUS Solutions Inc.

Figure 19: Chiller Energy Consumption During Monitoring Period



Source: TERSUS Solutions Inc.

For a baseline of how the TERSUS machine compared with traditional laundry, data was collected at a local laundromat. Traditional laundry is broken into two sections: the water washing machine and the gas dryer. The machine make and model were documented so the technical specifications from the machines manufacture could be downloaded. Using these documents, the per cycle energy usage was calculated and compared, tables 1 and 2

The washer runs on 230V service and uses 6.2 Amps of power. With an average cycle time of 30 minutes, the washer has a power consumption of 0.7 kWh per cycle. More energy is used in the drying phase, which involves natural gas for drying and electricity for the controls. The dryer cycle time during this demonstration was 45 minutes. The specific dryer was rated for 73,000 British thermal units per hour (BTU/hr), which results in 16 kWh per cycle. The dryer was rated to use 9 Amps of 240V service for controls, resulting in 1.62 kWh per cycle. Combined, the dryer uses a total of 17.6 kWh per cycle.

Table 1: TERSUS AA-75 Machine Energy Snapshot

Machine	Rated Capacity	Cycle time (dry to dry)	Total Energy consumption
TERSUS AA-75 Machine	75 lbs	45 mins	38.9 kWh
Totals	**75 lbs**	45 mins	38.9 kWh

Source: TERSUS Solutions Inc.

Table 2: Water Wash Energy Snapshot

Machine	Rated Capacity	Cycle time	Total Energy Consumption
Dexter Washing Machine	30 lbs	30 mins	0.7 kWh
Speed Queen Dryer	30 lbs	45 mins	17.6 kWh
Totals	30 lbs	75 mins	18.3 kWh

Source: TERSUS Solutions Inc.

To compare the water washing process to the TERSUS liquid CO_2 process, the same amount of laundry would need to be processed. The easiest comparison is 150 pounds and demonstrates both machines running at full capacity for multiple loads. To process 150 pounds of laundry the TERSUS machine would require two cycles while the water washing process would need five cycles. Tables 3-6 below show the water usage, operational time, energy usage, and throughput for the TERSUS machine versus the water washing machine and dryer.

Table 3: Water Comparable Poundage Energy Use

Machine	Energy Consumption	Cycle Time	3 cycle Energy Consumption	3 Cycle Time
Dexter Washing Machine	0.7kWh	30min	3.5kWh	150min
Speed Queen Dryer	17.6kWh	45min	88kWh	225min
Total	18.3kWh	75min	91.5kWh	375min

Source: TERSUS Solutions Inc.

Table 4: Time Comparison of 150 Pounds

TERSUS AA-75	90 minutes
Water Wash	375 minutes
Efficiently Gain	76%

Source: TERSUS Solutions Inc.

Table 5: Energy Comparison of 150 Pounds

TERSUS AA-75	77.8 kWh
Water Wash	91.5kWh
Efficiently Gain	15%

Source: TERSUS Solutions Inc.

When comparing the two styles of laundry, the throughput per hour for the operation can show gained efficiencies. The TERSUS machine is capable of 100 lbs/hr. The traditional water method given one washer and dryer of laundromat size will complete 24 lbs/hr (Table 6). The TERSUS AA-75 has 4.1 times the throughput of laundromat washers.

Table 6: Throughput Comparison

TERSUS AA-75	100 lbs/hr
Water Wash	24 lbs/hr
Efficiently Gain	76%

Source: TERSUS Solutions Inc.

TERSUS AA-75 Compared to Industrial Laundry Facility

TERSUS Solutions currently owns and operates a laundry service in Denver, Colorado. At this facility, TERSUS used larger capacity water process machines to clean large volumes of textiles. Comparing the TERSUS AA-75 machine to the water process machines in this facility would more closely compare to an industrial laundry service provider. The equipment used in that facility are listed below, while Table 7 provides the energy usage and time per cycle. 75 lbs. rated Wascomat EX677CL and 82 lbs. rated Wascomat DL83

Table 7: Industrial Laundry Water Energy Snapshot

Machine	Rated Capacity	Cycle time	Total Energy Consumption
Wascomat EX677CL	75 lbs	35	1.4 kWh
Wascomat DL83	82 lbs	50	36 kWh
Totals	75 lbs	85 mins	37.4 kWh

Source: TERSUS Solutions Inc.

When machines of this size are compared to the TERSUS AA-75 machine, the energy used is very comparable. The TERSUS AA-75 machine results in 38.9 kWh while the water cycle dry-to dry results in 37.4 kWh. The significant difference between the two processes is in the throughput rate which matters greatly in a laundry plant. Table 8 compares the throughput with the TERSUS AA-75.

Table 8: Industrial Laundry Throughput Comparison

TERSUS AA-75	100 lbs/hr
Wascomat Water Wash	52 lbs./hr.
Efficiently gain	48%

Source: TERSUS Solutions Inc.

The throughput of laundry is almost twice as high than the water process setup.

During a standard 8-hour workday, the Wascomat water wash can complete six cycles equaling 450 lbs of laundry. The TERSUS AA-75 can complete 11 cycles totaling 850 lbs. of laundry.

Cleaning Validation Results (HP White Results)

Ballistic Vest Results

Ballistic testing was conducted on the MTV ballistic body armor vests and the helmets. The MTV vests were conducted using standards MIL-STD-662F before cleaning. After cleaning MIL-STD-662F (MODIFIED) and PD/IMTV/2990-07-07 were used. For the Helmets, standard PER IOP-PED-003 was used before the cleaning. After the cleaning, standards IOP-PED-003 and FQ/PD-06-35C were used. Following are the V50 ballistic testing result summaries for the MTV Vests Initial and after cleaning a given number of times.

The TERSUS liquid carbon dioxide process is designed to take advantage of the natural properties of liquid carbon dioxide and use them for cleaning. For ballistic vests, there are two main advantages of using liquid carbon dioxide. The first advantage to the process is eliminating the need for a dryer. Since carbon dioxide is a gas at atmosphere pressures, the carbon dioxide evaporates and leaves the garments dry straight out of the machine. No heat is required and thus no dryer. The second advantage is the natural affinity of carbon dioxide which removes oil-based stains and body oils. Lastly, the vests do not have to be disassembled for cleaning, alleviating the time consuming and difficult task of removing the ballistic panels from the carrier. This allows for easy field cleaning of the MTV vests.

With these advantages, the TERSUS liquid carbon dioxide system becomes the best way to clean MTV vests, particularly the collars. After extended use, the yokes become dirty, oily and unpleasantly odorous. This results in many complaints. With the low viscosity and surface tension of liquid carbon dioxide, the TERSUS system can remove the body oils from the vests, especially the yokes, without the need to add detergents or heat. Detergents have the potential to degrade the Kevlar if not completely washed out. Using heat to remove water, as in traditional laundry processes, can degrade the Kevlar. If not properly dried, mold and mildew can form within the Kevlar. Furthermore, when tumbling the collars in the dryer, the loose Kevlar panels inside have a higher potential to fold over, leaving areas without as much protection. This is not only true of the yokes but any of the Kevlar panels throughout the Kevlar vest.

Figures 20 and 21 show an MTV vest before and after being cleaned with the TERSUS liquid carbon dioxide process.

Figure 20: Dirty MTV Vest

Source: TERSUS Solutions Inc.

Figure 21: Dirty MTV Vest Collar

Source: TERSUS Solutions Inc.

The results after processing in the TERSUS AA-75 (Figures 22 and 23).

Figure 22: Cleaned MTV Vest

Source: TERSUS Solutions Inc.

Figure 23: Cleaned MTV Vest Collar

Source: TERSUS Solutions Inc.

The body oils contaminating the yoke area were removed. TERSUS was informed that after the demonstration period, when the yokes were able to be cleaned, the number of complaints dropped significantly. This was stated by the warehouse manager and insurance manager of the garments. Cleaning the MTV vests with TERSUS greatly improves the comfort of the garments, by the removal odors and body oils that can cause associated rashes and itchiness. Not only does the TERSUS process clean the MTV vests very well but the process maintains the ballistic properties of the Kevlar.

As shown in Tables 9 and 10, the TERSUS CO2 process is very gentle on the ballistic vests and can keep them operating at their maximum potential. See Appendix F for HP White test reports.

Table 9: MTV Vest V50 Baseline Summary

Sample Number	V50	High Partial	Low Complete	Range of Results	Range of Mixed
HPW-1	1708	1711	1702	64	9
HPW-2	1689	1709	1704	97	5
HPW-3	1750	1771	1714	79	57
HPW-4	1655	1689	1632	91	57

Source: TERSUS Solutions Inc.

Table 10: MTV Testing After TERSUS Cleaning

Sample	Condition	Cycles	V50	High Partial	Low Complete	Range of Results	Range of Mixed
19F	USED	5	1691	1717	1638	88	79
19B	USED	5	1786	1799	1796	112	3
20F	NEW	5	1752	1797	1698	104	99
20B	NEW	5	1802	1794	1780	71	14
21F	NEW	10	IC	2064	1902	-	162
21B	NEW	10	1753	1773	1748	71	25
22F	NEW	20	1742	1789	1697	99	92
22B	NEW	20	1832	1822	1840	117	0

Source: TERSUS Solutions Inc.

Helmets were also tested in the TERSUS machine to observe the potential for cleaning them in CO_2 (Tables 11 and 12). Appendix F for HP White test reports.

Table 11: Helmet V50 Baseline Testing

Sample Number	V50	High Partial	Low Complete	Range of Results	Range of Mixed
HPW-1	1911	1902	1920	18	0

Source: TERSUS Solutions Inc.

Table 12: Helmet V50 After TERSUS Cleaning

Sample	Condition	Cycles	V50	High Partial	Low Complete	Range of Results	Range of Mixed
32	New	10	2049	2028	2069	41	0
33	New	20	1874	1892	1864	103	29
34	New	30	1839	1860	1842	110	19

Source: TERSUS Solutions Inc.

The results for the other garments tested during the demonstration period are provided in Tables 13-19 and Figures 24-31. See Appendix F for full HP White test results.

Table 13: HP White Results For ASTM D2261-2013 Tongue Tearing Strength

Sample	Average Tear Strength (N)		
	New	Water	CO_2
New Sleep System (0 Cycles)	26.6		
New Sleep System (10 Cycles)		35.35	35.00
New Sleep System (20 Cycles)		34.74	30.70
New Sleep System (30 Cycles)		35.80	28.35
New Poncho (0 Cycles)	38.75		
New Poncho (10 Cycles)		28.05	44.60
New Poncho (20 Cycles)		31.60	23.70
New Poncho (30 Cycles)		43.45	25.40
Goretex Jacket (0 Cycles)	29.2		
Goretex Jacket (10 Cycles)		29.35	33.90
Goretex Jacket (20 Cycles)		28.05	32.75
Goretex Jacket (30 Cycles)		27.20	34.40
Goretex Trouser (0 Cycles)	30.95		
Goretex Trouser (10 Cycles)		26.80	32.25
Goretex Trouser (20 Cycles)		26.35	27.75
Goretex Trouser (30 Cycles)		26.40	28.70

Source: TERSUS Solutions Inc.

Table 14: HP White Results For ASTM D2261-2013 Tongue Tearing Strength

Sample	Average Tear Strength (N)
New Tent (0 Cycles)	34.25
New Tent (10 Cycles) CO_2	24.10
New Tent (20 Cycles) CO_2	18.75
New Tent (30 Cycles) CO_2	25.40
Used Tent (0 Cycles)	11.50
Used Tent (1 Cycle) CO_2	11.80
New FROG (0 Cycles)	67.1
New FROG (10 Cycles) CO_2	62.20
New FROG (20 Cycles) CO_2	54.15
New FROG (30 Cycles) CO_2	63.15
Used FROG (0 Cycles)	42.05
Used FROG (1 Cycle) CO_2	60.55

Source: TERSUS Solutions Inc.

Table 15: HP White Results For ASTM E1164-12 Chromaticity Test

Sample	x	y	L(Y)
New Sleep System, 0 Cycles	0.361	0.369	5.380
New Sleep System, #8, Water, 10 Cycles	0.362	0.369	5.130
New Sleep System, #91, CO_2, 10 Cycles	0.363	0.369	5.350
New Sleep System, #10, Water, 30 Cycles	0.362	0.370	4.500
New Sleep System, #7, CO_2, 30 Cycles	0.357	0.366	5.760
New Poncho, 0 Cycles	0.368	0.377	7.11
New Poncho, #64, Water, 10 Cycles	0.350	0.377	6.850
New Poncho, #61, CO_2, 10 Cycles	0.352	0.375	6.910
New Poncho, #66, Water, 30 Cycles	0.348	0.375	6.320
New Poncho, #63, CO_2, 30 Cycles	0.350	0.377	6.040
New Goretex Jacket, 0 Cycles	0.366	0.389	18.83
New Goretex Jacket, #74, Water, 10 Cycles	0.362	0.397	17.470
New Goretex Jacket, #71, CO_2, 10 Cycles	0.363	0.400	18.210

Sample	x	y	L(Y)
New Goretex Jacket, #76, Water, 30 Cycles	0.364	0.399	18.560
New Goretex Jacket, #73, CO_2, 30 Cycles	0.366	0.403	18.780
New Goretex Trousers, 0 Cycles	0.369	0.393	15.99
New Goretex Trousers, #84, Water, 10 Cycles	0.363	0.398	18.240
New Goretex Trousers, #81, CO_2, 10 Cycles	0.361	0.395	19.290
New Goretex Trousers, #86, Water, 30 Cycles	0.366	0.401	17.890
New Goretex Trousers, #83, CO_2, 30 Cycles	0.368	0.397	19.340
New Tent, 0 Cycles	0.350	0.362	5.37
New Tent, CO_2, 10 Cycles	0.363	0.377	6.40
New Tent, CO_2, 30 Cycles	0.360	0.376	6.82
Used Tent, 0 Cycles	0.354	0.373	8.62
Used Tent, CO_2, 1 Cycle	0.357	0.375	7.90

Source: TERSUS Solutions Inc.

Table 16: HP White Results for ASTM F1868 Thermal and Evaporative Resistance Tests

Sample	R_{ct}	R_{cf}	I_t
New Sleep System, #8, Water, 10 Cycles	0.955	0.88	6.157
New Sleep System, #91, CO_2, 10 Cycles	0.971	0.896	6.262
New Sleep System, #9, Water, 20 Cycles	1.188	1.113	7.66
New Sleep System, #92, CO_2, 20 Cycles	0.974	0.9	6.284
New Sleep System, #10, Water, 30 Cycles	0.997	0.922	6.43
New Sleep System, #7, CO_2, 30 Cycles	0.988	0.914	6.375
Used/Dirty Sleep System, #90, Water, 1 Cycle	0.718	0.644	4.633
Used/Dirty Sleep System, #89, CO_2, 1 Cycle	0.747	0.672	4.816

Source: TERSUS Solutions Inc.

Table 17: HP White Results for ASTM D6413 Flame Resistance Tests

Sample	After Flame (sec)	After Glow (sec)	Char Length (mm)
New FROG, 0 Cycles	0.0	0.0	22.0
New FROG, CO_2, 10 Cycles	0.0	0.2	25.0
New FROG, CO_2, 20 Cycles	0.0	0.25	23.0
New FROG, CO_2, 30 Cycles	0.0	0.2	25.5
Used FROG, 0 Cycles	0.0	0.0	20.5
Used FROG, CO_2, 1 Cycle	0.0	0.2	22.5

Source: TERSUS Solutions Inc.

Table 18: HP White Results for AATCC 22-2010 Water Repellency Spray Test

Sample	Water	CO_2
New Sleep System (10 Cycles)	100	97
New Sleep System (20 Cycles)	100	90
New Sleep System (30 Cycles)	100	90
New Poncho (10 Cycles)	50	50
New Poncho (20 Cycles)	50	60
New Poncho (30 Cycles)	88	50
Goretex Jacket (10 Cycles)	100	70
Goretex Jacket (20 Cycles)	100	60
Goretex Jacket (30 Cycles)	100	67
Goretex Trouser (10 Cycles)	100	80
Goretex Trouser (20 Cycles)	100	73
Goretex Trouser (30 Cycles)	100	63

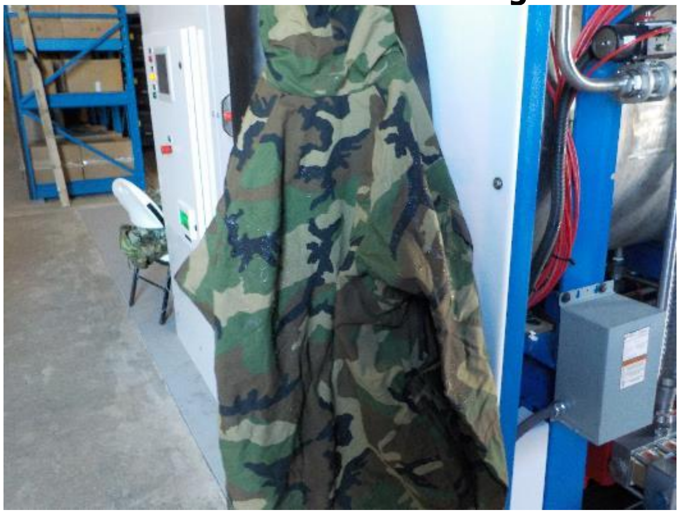
Source: TERSUS Solutions Inc.

Table 19: HP White Results for AATCC 22-2010 Water Repellency Spray Test

Item	Result
New Tent (0 Cycles)	100
New Tent (10 Cycles) CO_2	95
New Tent (20 Cycles) CO_2	90
New Tent (30 Cycles) CO_2	70

Source: TERSUS Solutions Inc.

Figure 24: GORE Jacket Pre-Cleaning DWR Results



Source: TERSUS Solutions Inc.

Figure 25: GORE Jacket Post Cleaning DWR Results

Source: TERSUS Solutions Inc.

Figure 26: GORE Jacket Seam Tape Integrity

Source: TERSUS Solutions Inc.

Figure 27: Sleep System Pre-Cleaning

Source: TERSUS Solutions Inc.

Figure 28: Sleep System Bag Pre-Cleaning

Source: TERSUS Solutions Inc.

Figure 29: Sleep System Bag Post Cleaned

Source: TERSUS Solutions Inc.

Figure 30: Sleep System Post Cleaned

Source: TERSUS Solutions Inc.

CHAPTER 5:
Analysis and Impact

Achieving Goals

At the start of this project TERSUS Solutions established several technical and environmental related goals, all of which were achieved during this demonstration project.

TERSUS Solutions demonstrated improved operational efficiency (76 percent higher throughput efficiency) and 15 percent utility savings compared to traditional water-based cleaning methods. The TERSUS Solutions liquid CO_2-based cleaning system showed savings of 117.5 gallons of water per every 150 pounds of laundry. Additionally, TERSUS Solutions confirmed the viability of cleaning and maintaining the ballistic properties of MTV ballistic vests without the use of water or chemicals. Unpleasant odors and oils from heavy use were removed to provide a clean and comfortable vest to wear.

Impact

The Tersus Equipment excels at cleaning and decontaminating difficult and delicate textiles and technical garments. These items are rarely laundered, if ever, which presents challenges for comfort and overall satisfaction. A TERSUS machine installed in the requisition bases across the country could result in a drastic increase in overall satisfaction of the re-requisitioned garments when worn, especially for heavy use items such as the MTV ballistic vests. This impact would not just affect the users of the vests. Satisfaction throughout the entire handling process would increase due to operators not having to handle un-cleaned items. Additionally, requisition officers would see an increase in overall job satisfaction by not having to issue dirty garments to service personnel. This would alleviate issues with the MTV vests due to odors, itchiness from body oils or other comfort and health related complaints. While this may not be able to be quantified into a monetary number, job satisfaction and health can result in a more productive operation. From the user perspective, when odors are not present and there is less risk of skin irritation from use, the service personnel will see an increase of comfort while wearing.

Additionally, there are significant energy and water savings with the TERSUS platform. Each Tersus machine can replace two large commercial sized washers and dryers or three standard commercial sized washers and dryers. Water savings would average about 16.7 (gal/water wash cycle), totaling about 100 gal/day/machine that was replaced doing six water wash cycles per day. These water and energy savings would scale as Tersus machines replaced water washers and dryers on Naval bases across the country.

CHAPTER 6: Next Steps

Continued Testing and Validation

Some key cleaning benefits of the TERSUS Solutions' CO_2 cleaning process were not thoroughly explored during this demonstration. Opportunities to validate cleaning of fire-retardant garments and oily rags would allow to further distinguish TERSUS Solutions' CO_2 cleaning process as superior. During the demonstration period, TERSUS was not able to obtain the federal fire-retardant garments, base security garments and oily rags to conduct verified testing.

Examination of the HP White testing results shows reduced water repellency after washes with the liquid CO_2 cleaning process. TERSUS Solutions has done extensive testing on applying DWR and have had very favorable results. Some of the garments chosen may not need as many washes as were conducted in this demonstration, such as the tents. Nevertheless, after the demonstration period of this project TERSUS Solutions developed a successful DWR application process which could offset the effect to water repellency. TERSUS Solutions would welcome the prospect of being able to validate this in collaboration with the Department of the Navy.

Another area that would benefit from additional validation would be energy studies regarding the TERSUS AA-75 machine and associated equipment. This installation was a very isolated situation. The only equipment that required power and energy in the area was the TERSUS setup. In a facility where there is a full-on laundry site, the other pieces of equipment will also be using energy for heating. The boiler is the highest energy user of the TERSUS equipment. Since the machine was the only item connected to this, the boiler was relatively small. When steam is used across an entire plant, the boiler is sized up and there are many efficiencies that can be gained. This should be analyzed to determine what the effect is on the boiler portion of the energy used.

Establishing the feasibility to use the TERSUS AA-75 in areas where water is scarce, such as forward operating bases, would be another next step in a continued partnership with the Department of the Navy. Further discussions on the true needs required in either scenario could also lead to redesigns or size adjustments of the machine and associated equipment. TERSUS Solutions is confident that continued development would lead to many more beneficial outcomes and hopes to be given the opportunity to do so with the Department of the Navy.

LIST OF ACRONYMS

Term	Definition
°F	Degrees Fahrenheit
BTU/hr	British thermal units per hour
CO_2	Carbon dioxide
DWR	Durable water repellancy
kWh	Kilowatt-hours
L	Liters
lbs	pounds
lbs/hr	Pounds per hour
MTV	Modular tactical vests

APPENDICES

The following appendices are available under separate cover (Publication Number CEC-500-2020-056-APA-H) by contacting Kevin Mori at Kevin.Mori@energy.ca.gov.

- Appendix A - CATEX
- Appendix B - CRADA
- Appendix C - Safety Manual
- Appendix D - Machine Technical Specifications
- Appendix E - Test Matrix
- Appendix F - HP White Test Results
- Appendix G - Ballistic Testing
- Appendix H - Raw Data