Summary of Impacts from CO2-Based Cleaning Process on Firefighter Turnout Gear: Moisture Barrier & Thermal Liner Performance after 30 Cleaning Cycles

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Background

CO2-based cleaning technology is an effective decontamination technology that is now available for advanced and specialized cleaning of firefighter gear, including coats, pants, hoods, gloves, leather boots and other related clothing articles. Emergency Technical Decon (ETD) offers this innovative cleaning technology as North America's first fully verified Independent Service Provider (ISP) utilizing liquid CO2 technologies by the NFPA 1851-2020 standard at its Eagan, MN facility. Based on third party cleaning verification testing at UL in accordance with NFPA 1851 test methods and requirements, the CO2 based cleaning system has generated outstanding cleaning and decontamination results for semi-volatile organic compounds (SVOCs), heavy metals and bacteria. Another key feature of this technology is minimizing its impact on the performance properties of these articles from repeated cycles of cleaning and decontamination. In an earlier paper[1], detailed durability test results on the outer shell of firefighter turnout gear were presented which showed insignificant impacts from thirty (30) CO2 cleaning cycles. This paper extends this earlier work to summarize test results from evaluations of CO2 liner cleaning cycles on moisture barrier and thermal liner material after multiple cleanings.

Test Methodology

The suggested annex procedures provided in NFPA 1851 in A.7.3.7.3 where panels measuring 26” x 26” of outer shell material with hemmed edges were used for evaluating changes in outer shell performance properties after 30 cycles of CO2 cleaning. The test evaluation procedures followed are summarized in Table 1. Some samples included seams, trim, and labels to also evaluate the effects of repeated cleaning on these components. Each panel was photographed and combined with other clothing and ballast material to provide a representative load weighing approximately 35 lbs. Note that because the articles processed are dry at cycle completion, each-cycle method represents both cleaning and ‘drying’ of the articles. The typical process cycle length is 60 minutes. As part of this methodology, test samples were examined after each set of ten (10) cleaning cycles to observe and measure certain properties related to outer shell cleaning durability. These included water droplets spread on the material surface at different locations, the measurement of color coordinates using a spectrophotometer, and appearance of samples having trim and labels components. At the completion of all 30 cleaning cycles, the samples are shipped to UL for assessment.

Table 1 – Tests Methods Followed for This Evaluation

Test Method	Title
ASTM D5034	Breaking strength
ASTM D5587	Tear resistance
ASTM D1683	Seam strength
AATCC 42	Water absorption resistance
AATCC 135 (1, V, Ai	Cleaning shrinkage
ASTM D6413	Flame resistance (after flame, char length)
ISO 17241	Thermal protective performance (TPP)
ASTM F1868, Pr. C	Total Heat Loss (THL)

UL Durability Test Results – Thermal Barrier

The results of the UL tests are summarized in Table 2 and show **insignificant** changes to key thermal barrier parameters of the turnout gear, which include the NFPA 1971 requirements, baseline values for new (uncleaned) samples, results measured after 30 cycles of CO2 cleaning, and the percent change for the multi-cleaned samples from the baseline values.

Breaking Strength, Tear Resistance and Seam Strength

The breaking strength of a fabric also can be called tensile strength, which refers to the maximum tensile force when the specimen is stretched to break. Warp and fill (also called weft) refer to the orientation of woven fabric. The warp direction refers to the threads that run the length of the fabric. The fill, or weft, refers to the yarns that are pulled and inserted perpendicularly to the warp yarns across the width of the fabric. Examination of the results in Table 2 show that the breaking strength, tear resistance and shear strength showed minimal changes to their baseline values after 30 CO2 process cycles. It is significant to note that tear resistance (warp and fill) and seam strength values increased after 30 cycle cleaning process.

Table 2 – UL Durability Test Results after 30 CO2+ Cleaning Cycles – Thermal Liner

Property	Requirement	Units	Baseline	Cleaned 30X	% Better Than Requirement
Tear Resistance - Warp	>= 22	N	103	172	682%
Tear Resistance - Fill	>= 22	N	88	122	455%
Seam Strength	>=334	N	260	490	47%
Cleaning Shrinkage - Warp	<= 5	%	na	4%	20%
Cleaning Shrinkage - Fill	<= 5	%	na	3%	40%
Afterflame - Warp	<=2	sec	0.1	0.2	90%
Afterflame - Fill	<=2	sec	0.1	0.1	95%
Char length - Warp	<=100	mm	8	7	93%
Char length - Fill	<=100	mm	5	6	94%

After flame and Char Length

After-flame time is the time during which the material continues to flame after the ignition source has been removed or extinguished. Char Length is the length in inches of fabric destroyed by the flame. The occurrence of melting or dripping, if any, is also recorded. Five tests are performed, and the results are averaged and reported as the final test result. The data reported in Table 2 shows after flame and char length in both the warp and fill directions well below the action levels. In addition, no melting or dripping was reported.

UL Durability Test Results – Moisture Barrier

The results of the UL tests for moisture barrier - Stedair Gold (SAG) tested by UL are summarized in Table 3. A review of this table show that the SAG samples showed excellent values for tear resistance, seam strength and char length test. After-flame testing results from the UL evaluation showed inconsistent and unexpected test results. Because of the unusual nature of these results, it was decided to repeat the flame resistance testing on the SAG samples and evaluate an additional commonly used product from Gore - Crosstech Black 2F.

Table 3 – UL Durability Test Results after 30 CO2 Cleaning Cycles – Stedair Gold

Property	Requirement	Units	Baseline	Cleaned 30X	% Better Than Requirement
Tear Resistance - Warp	>= 22	N	93	88	300%
Tear Resistance - Fill	>= 22	N	85	84	282%
Seam Strength	>=334	N	551	437	31%
Char length - Warp	<=100	mm	60	66	34%
Char length - Fill	<=100	mm	73	92	8%

Supplemental Flame Resistance Testing of Moisture Barrier Samples

A follow-on study was undertaken to verify the earlier flame resistance test data generated by UL. These tests were conducted internally at the ETD facility in Eagan, MN following the specifications of ASTM D6413 – Standard Test Method for Flame Resistance of Textiles (Vertical Test) with the following exceptions detailed in Table 4. A photo of the burn box used for this study is presented in Figure 2.

Figure 3 shows a photo of a sample mounted in the burn box with the flame just prior to ignition, during the sample burn and after removal of the flame. Using the test methodology outlined in ASTM D6413 using the burn box shown in Figure 2, a series of flammability test evaluations were conducted on two types of moisture barrier materials: Stedair Gold, and Gore Crosstech 2F. Objective: to identify changes in key fabric flammability metrics as they relate to the number of CO2 cleaning cycles. The flammability metrics included:

- After flame time – visible burn time after removal of flame source
- Afterglow time – visible glowing after removal of flame source
- Char length – distance from fabric leading edge showing visible fabric damage from an applied force
- Melting – liquification of material from the flame
- Dripping – liquified product drops from sample.

Table 4 – Differences between ASTM 6413 Test Method and Method Used for This Survey

Item	Units	ASTM 6413	ETD/CCT Burn Test Chamber
Chamber Width	mm	308 +/- 25	610
Chamber Depth	mm	308 +/- 25	279
Chamber Height	mm	762 +/- 25	775
Burner Flame Ignition Method	na	Actuated CH4 solenoid valve opened and gas ignited by pilot flame located adjacent to burner tip	CH4 gas gas manually opened and burner ignited by propane lighter - no fixed pilot flame
Flame Height Gauge	na	Gage affixed to burner	Gage marked on sample holder
Sample Ignition Method	na	Sample ignited by flame ignition started with CH4 solenoid valve opening	Sample ignited by manually moving flame under sample
Sample Burn Timing	na	Automatic - flame impingment timer	Exterior timer backed up by video of each test
Number of samples	na	Average of 5 samples	Average of 1-2 samples

Samples were tested in the burn test chamber after they were subjected to a range of CO2 cleaning cycles: 1, 2, 3, 5, 10, 15, 20, 25, 30 => 9 different test periods. Samples of each moisture barrier were sewn together – one cut in the 'warp' direction, one cut in the 'fill' direction - with the MB part of sample facing each other. Two sets of samples were introduced to the cleaning vessel for each 9 test periods evaluated. => 18 samples for each MB type – Stedair Gold/W.L. Gore Crosstech Black. At the end of the 1st wash, two samples of each type were removed from the cleaning vessel, the remainder were left in the vessel for the next cleaning cycle. At the end of the 2nd wash, two more samples were removed, etc. Each CO2 Liner wash cycle was run to completion, though the cleaning vessel door was only opened to remove samples after the appropriate test cycle number. The CO2-based liner cleaning process consisted of four (4) wash/rinse steps. After the samples are removed from the chamber they are separated from the sandwich and cut to size for the test – 3" x 12". Samples are stored in air-conditioned room out of the light for at least 2 hours (per ASTM D1776) and NFPA 1851 2020 Edition Standard. Then samples were placed in paper envelopes for storage until burn test Based on the guidelines in ASTM 6413 the following 'burn' protocol was used:

1. Sample removed from storage envelope.
2. Sample ID – Stedair Gold – wash cycle 5 – sample #1 – Fill – (SAG-F-5.1).
3. Sample mounted on sample holder.
4. Photos before flame test taken on both fabric and MB sides.
5. Subjected to flame for 12 seconds.
6. After flame and afterglow times noted.
7. Evidence of sample melting or dripping noted.
8. Video of flame burn taken.
9. Photos after flame test taken on both fabric and MB sides.
10. Samples returned to envelop for subsequent testing and examination.

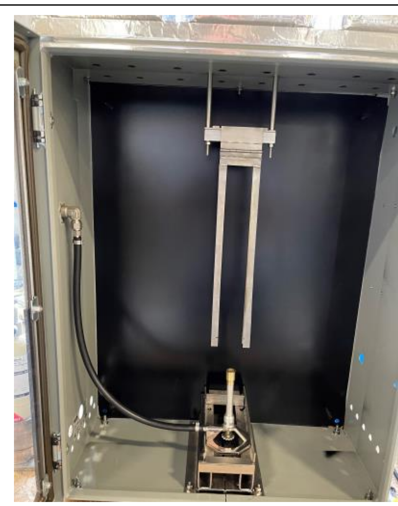

Figure 2 – Burn Box Used for ETD Tests following ASTM D6413 Protocols

After conducting the flame studies, char lengths of the samples evaluated were determined based on protocols outlined in ASTM D6413.

A summary of the flammability tests for the Stedair Gold and Gore Crosstech Black are presented in Table 5 for samples exposed to 5, 10, 25 and 30 CO2 Liner Wash Cycles. Examination Table 5 below shows that the flammability evaluations showed no measurable difference from the As Received (AR) values. Note that times less than 1 second were not reported as they are insignificant to the overall result. Furthermore, no melting or dripping was observed for any of the sample tests. The char length data for the Stedair Gold samples showed minimal changes to those of the AR values. The Gore samples showed an increase in the char length though only the value obtained after 30 wash cycles exceeded the standard, and that by less than 10%.

Hence, based on the data reported in Table 5, we conclude that the ETD CO2 Liner Cleaning Cycle generated minimal flammability impacts based on ASTM D6430 criteria.

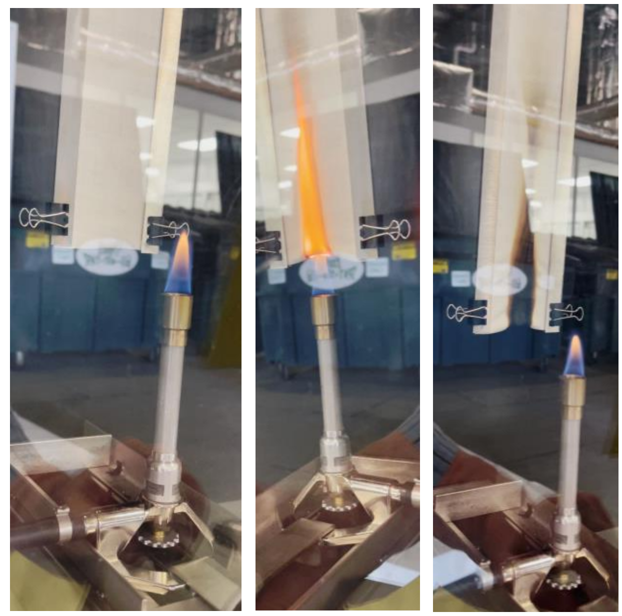

Figure 3 – Flame Resistance Test Sequence – Before ignition (left), During Ignition (center), After Removal of Flame (Right)

Table 5 – Flammability Test Results for Moisture Barrier Samples Exposed to Successive CO2 Liner Cleaning Cycles

Measurement	Direction	Acceptance Criteria	Steadair Gold - Samples Sewed back to back					Gore - Samples Sewed back to back				
			AR	5x	10x	25x	30x	AR	5x	10x	25x	30x
Afterflame time (sec)	Warp	Less than or equal to 2.0	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Fill		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
After glow time (sec)	Warp	na	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Fill		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Char length (mm)	Warp	Less than or equal to 100	19	19	19	25	28	81	60	97	89	97
	Fill		19	19	25	25	25	57	57	86	84	109
Melting (observed)	Warp	None	None	None	None	None	None	None	None	None	None	None
	Fill		None	None	None	None	None	None	None	None	None	None
Dripping (observed)	Warp	None	None	None	None	None	None	None	None	None	None	None
	Fill		None	None	None	None	None	None	None	None	None	None

Conclusions

The CO2 cleaning process not only yields excellent cleaning and decontamination efficacy based on its cleaning verification results, but these additional data also shows that the process does NOT adversely impact the inner layers (thermal liner and moisture barrier) of the turnout gear in any meaningful way. Those interested in better cleaning and toxin removal without damage to their gear should consider this option.

[1] Sorbo, N.W., 'Impact of CO2-Based Cleaning Technology on Firefighter Turnout Gear: Outer Shell Performance after 30 Cleaning Cycles', an internal report published by ETDecon, 21Aug2021.