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

Figure 1 - Example of test sample panel that was evaluated, outer (l), inner liner (r)

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, shown in Figure 1. 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.

UL Durability Test Results – Thermal Barrier

The results of the UL tests are summarized in Table 1 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.

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 (afterflame, char length)
ISO 17241	Thermal protective performance (TPP)
ASTM F1868, Pr. C	Total Heat Loss (THL)

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 CO_2 process cycles. It is significant to note that tear resistance (warp and fill) and seam strength values increased after 30 cycle cleaning process.

Afterflame and Char Length

Afterflame 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 afterflame and char length in both the warp and fill directions well below the action levels. In addition, no melting or dripping was reported.

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%

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. Afterflame testing results from the UL evaluation showed inconsistent and unexpected test results.

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%

Moisture Barrier Seam Strength Testing - Intertek

Testing of samples of moisture barrier seam were conducted by Intertek[2] following NFPA 1971-18 Seam Breaking Strength Test for two different moisture barrier materials – Crosstech 2F (black) and Stedair Gold subjected to 30X CO2 cleaning cycles and compared with their respective unwashed samples. The data for these tests is summarized in Table 4 and were conducted by Intertek in October 2021 [2].

Table 4 - Seam Strength Testing of Crosstech 2F and Stedair Gold Moisture Barriers after Thirty (30) CO2 Wash Cycles

	Crosstech 2F - Unwashed		**Crosstech 2F - CO2 Washed 30 Cycles**	
Seam Specimen	Seam Strength, N	Failure Type	Seam Strength, N	Failure Type
1	422	Fabric Tear near grip	456	Fabric Tear near grip
2	453	Fabric Tear near grip & along seam	412	Fabric Tear near grip
3	420	Fabric Tear near grip	422	Fabric Tear near grip
4	446	Fabric Tear near grip	450	Fabric Tear near grip
5	422	Fabric Tear along seam	416	Fabric Tear along seam
Avg	432.6		431.2	
StDev	15.6		20.3	
	Stedair Gold - Unwashed		**Stedair Gold - CO2 Washed 30 Cycles**	
Seam Specimen	Seam Strength, N	Failure Type	Seam Strength, N	Failure Type
1	348	Fabric Tear along seam	316	Fabric Tear along seam
2	324	Fabric Tear along seam	309	Fabric Tear along seam
3	310	Fabric Tear along seam	342	Fabric Tear along seam
4	322	Fabric Tear along seam	325	Fabric Tear along seam
5	327	Fabric Tear along seam	341	Fabric Tear along seam
Avg	326.2		326.6	
StDev	13.8		14.7	

Based on the data in Table 4, there was absolutely no impact of the laundering on the seam strength. For perspective, typically copious amounts of conventional washing either cause weakening of seams or cause shrinkage of the seams that has the impact of increasing the seam strength (but ultimately indicates other problems as the result of the washing). The CO2 cleaning process did neither.

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 which were believed to be spurious and inconsistent with the cleaning chemistry utilized. To validate these assumptions, additional 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 exceptions detailed in Table 5.

Table 5 - 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

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.

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

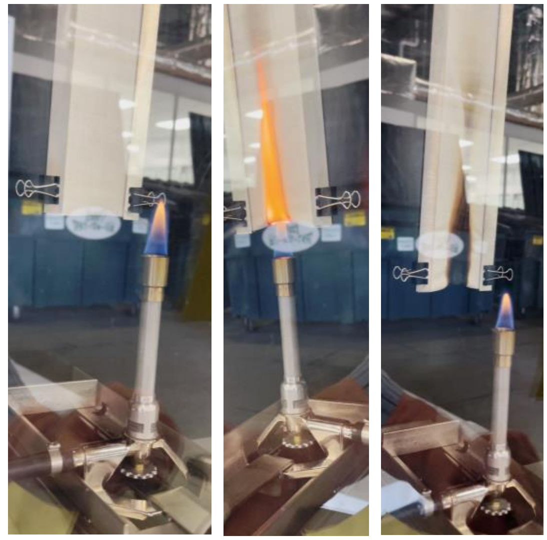

Figure 3 - Flame Resistance Test Sequence – Before ignition (left), During Ignition (center), After Removal of Flame (Right)

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:

- Afterflame 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.

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. Afterflame and afterglow times noted.
7. Evidence of sample melting or dripping noted.
8. Video of flame burn taken.
9. Photos afterflame test taken on both fabric and MB sides.
10. Samples returned to envelop for subsequent testing and examination.

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 6 for samples exposed to 5, 10, 25 and 30 CO2 Liner Wash Cycles. Examination Table 6 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 6, we conclude that the ETD CO2 Liner Cleaning Cycle generated minimal flammability impacts based on ASTM D6430 criteria.

Table 6 - 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

Extended Flame Resistance and Moisture Penetration Testing of Moisture Barrier Samples

Enhanced cleaning chemistries and process have been developed to improve the cleaning performance in inner liners of the firefighter turnout gear. As the moisture barrier is the most delicate part of the gear with respect to changes in cleaning process, additional testing of moisture barrier samples subjected to this enhanced liner cleaning process was conducted.

Samples of the following moisture barriers were tested:

- Crosstech 2F (black);
- Stedair Gold;
- Stedair 3000;
- Stedair 4000.

The CO2 cleaning process used was one developed specifically for liners, which utilized a proprietary additive CoolCare™ as a supplemental cleaning agent.

Further, to provide the most robust test scenario for these samples, successive CO_2 cleaning cycles up to fifty (50) were conducted. Samples of each of the moisture barriers were prepared and sewn to new samples of thermal liners as shown in Figure 4.

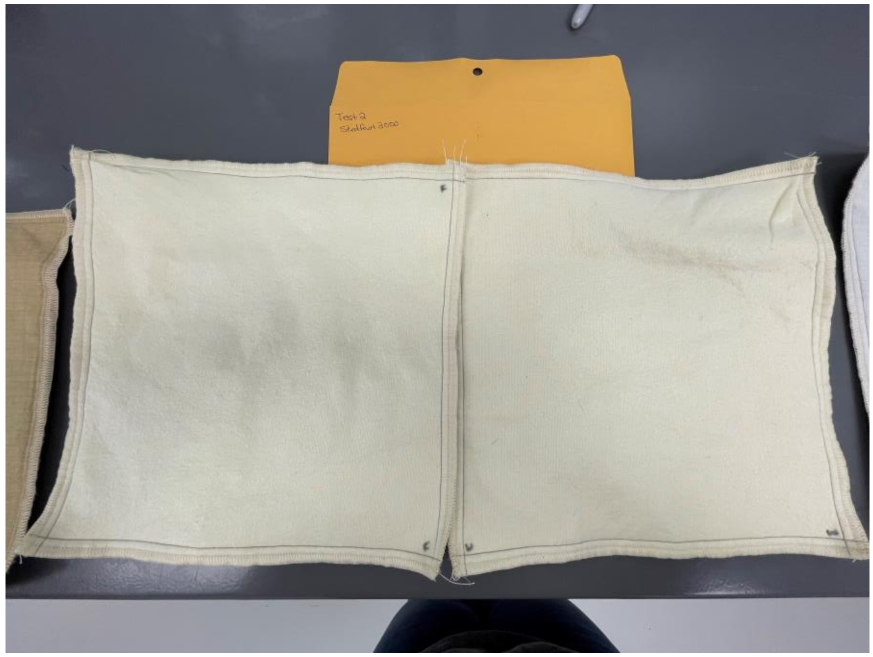

Figure 4 - 'Sandwich' samples used for Moisture Barrier Evaluation – Stedair – Steadfast 3000 shown.

To simulate conditions an inner liner would experience in the cleaning system the following protocol was developed and used:

1. Each moisture barrier sample was sewn together with a new piece of thermal liner – forming a 12"x12" 'sandwich', as shown in Figure 4.
2. A cleaning load was developed to mirror a typical loading in the CO_2 cleaning system with:
    a. The sandwich samples were inserted into a test standard garment bag used for containing other articles in the cleaning process – shown in Figure 5.
    b. The garment bag with the samples inside was loaded into successive layers of load ballast (out-of-service liners which were clean) such that the total wash load of an average of 28.4 lb, shown in Figure 6.

Figure 5 - 'Sandwich' Samples in garment bag for extended cleaning tests.

Figure 6 - Samples in garment bags mixed with liners for ballast.

3. A test sequence was developed to generate samples for up to fifty (50) successive washes, which was divided into nine (9) cleaning test groups, shown in Table 7. Each test group consisted of multiple CO_2 cleaning cycles which were run successively; cleaning test group #1 had 10 cleaning cycles, cleaning test group #2 had 5 cleaning cycles, etc.
4. As sandwich samples were removed from garment bags, additional ballast in the form of liners was added to the load to maintain a similar weight for all cleaning cycles. Typically, the load variance changed by less than 0.6 lbs.
5. At the conclusion of cleaning test group #9, those samples were subjected to fifty (5) cleaning cycles.

As before, the test load was generated with test samples along with ballast materials, and subjected to 10, 15, 20, 25,30, 35, 40, 45, and 50 successive cleaning cycles. At the end of each set of cycles, sample swatches were collected while the remaining samples were subjected to another group of cleaning cycles. At the conclusion of this test, samples of each of the four (4) moisture barrier samples were collected for flame resistance and moisture penetration tests using methods presented above. A total of nine (9) cleaning test groups were developed to generate these samples

For the flame resistance, emphasis was placed on samples subjected to fifty (50) successive enhanced liner cleaning processes as this is considered a 'worst case' most aggressive exposure to the samples. The flame resistance testing of samples subjected to fifty (50) enhanced liner cleaning chemistry cycles showed that: a) afterflame and afterglow parameters for all samples were below the criteria presented in Table 6 above; and b) no melting or dripping was recorded during these flame tests.

The moisture penetration tests were conducted on each of the samples detailed above and consisted of two types of evaluations:

- White light test – a light is shined on the back of the moisture barrier sample. If any light is shown to penetrate any part of the sample, that part of the sample is tested with a hydraulic test.
- The water penetration barrier evaluation consists of subjecting the test sample to a pressure of 1 psi for 15 seconds, as specified in NFPA 1851 Section 12.3. If any water is shown to penetrate the sample, this sample is considered a failure.

All samples outlined in Table 7 were tested and showed that <u>all test samples passed the water penetration tests, even those exposed to fifty (50) cleaning tests</u>.

Table 7 - Extended Flame Resistance / Moisture Barrier Sample Cleaning Scenario

	CO2 Cleaning Cycle Number		12"x12" Samples					Cleaning Test Load			
Cleanng Test Group	Start	End	Gore P.B.	SA 3000	SAG	SA 4000	Total per cleaning test	bag wt/test	No. Liners	wt/test (lb)	wt / test (lb)
1	1	10	18	18	18	18	72	12.8	8	16	28.8
2	11	15	16	16	16	16	64	12.0	8	16	28.0
3	16	20	14	14	14	14	56	11.2	9	18	29.2
4	21	25	12	12	12	12	48	10.3	9	18	28.3
5	26	30	10	10	10	10	40	9.5	9	18	27.5
6	31	35	8	8	8	8	32	8.7	10	20	28.7
7	36	40	6	6	6	6	24	7.9	10	20	27.9
8	41	45	4	4	4	4	16	7.0	11	22	29.0
9	46	50	2	2	2	2	8	6.2	11	22	28.2

Conclusions

The focus of this study was to determine the impact of the CO_2 cleaning process on the inner liners consisting of the thermal liner and moisture barrier, the most sensitive part of the firefighter turnout gear. This evaluation considered potential mechanical damage (breaking strength, tear resistance, seam strength), water absorbance, shrinkage, flame and thermal resistance, and water penetration for multiple moisture barriers exposed to up to fifty (50) cleaning cycles. The test data reported in this paper[3] show that the process does NOT adversely impact the inner layers (thermal liner and moisture barrier) of the turnout gear in any meaningful way. Further, given the durability results from the outer shell reported earlier, and the outstanding toxic organic decontamination capability of the CO_2 process reported previously, the CO_2 cleaning process should be strongly considered by those interested in better cleaning and toxin removal without damage to firefighter turnout gear.

For more information visit ETD's website www.etdecon.com and email ppeclean@etdecon.com.

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[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.

[2] Intertek Laboratory Report – NFPA 1971-18 Seam Breaking Strength Test – Modified, Job # G104819622, October 6, 2021.

[3] Sorbo, N.W., 'Firefighter Turnout Gear SVOC Cleaning Efficiency of CO2-Based Cleaning Process Compared to Traditional Water-Based Cleaning Methods', an internal report published by ETDecon, October 15, 2020.