Characterization of the Mechanical Trash Compactor Bag Removal Force

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Managing trash accumulation is a critical challenge in human space explorations since the trash volume and mass can significantly influence launch cost and operational efficiency. This study aids the development of a Mechanical Trash Compactor (Mpactor) by testing the removal force required to remove a "trash bag" from the Mpactor. To do this, a Pneumatic Pressure Mandrel System was designed to simulate the normal force trash would exerts on the trash bag and subsequently the sidewalls of the Mpactor. For various levels of sidewall normal force, the removal force required to remove the simulated trash bag from the Mpactor compaction chamber was measured. This testing is used to identify optimal bag materials. Additionally, testing was done on both the native stainless steel walls of the compaction chamber as well as the walls after being Teflon lined. Split-plot ANOVA, simple main effects analysis, Holm's post hoc comparisons for interaction, and sensitivity analyses were conducted to assess the influence of trash bag and sidewall materials on the required removal force. It was found that Teflon reduced the force required to remove the trash bag as well as reduced material-dependent variation in removal force. Testing showed that Teflon reduced the required removal force with a Polyvinylidene Fluoride , an unidentified Ethylene acrylate - Low Density Polyethylene copolymer, and a Polyvinyl Chloride all requiring significantly less removal force than the other materials tested.

Acronyms and Nomenclature

μ_s	=	Coefficient of static friction
η^2_p	=	Partial eta squared
A_1	=	Top box inner wall area
A_2	=	Bottom box inner wall area
A_T	=	Total box inner wall area
ANOVA	=	Analysis of Variance
b.PP	=	Black-dyed Polyropylene
c.PP	=	Clear Polyropylene
CEV	=	Crew Exploration Vehicle
df	=	Degrees of freedom
df_{error}	=	Degrees of freedom for error
EA-LDPE	=	an unidentified Ethylene acrylate – Low Density Polyethylene copolymer
ESM	=	Equivalent System Mass
F	=	F-statistic
F_R	=	Removal force (lbf)
F_{N1}	=	Top chamber wall normal force
F_{N2}	=	Bottom chamber wall normal force
f_1	=	Top wall and tubes static friction
f_2	=	Bottom wall and tubes static friction
lb_f	=	pound-force
Mpactor	=	Mechanical Trash Compactor

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MS_{effect}	=	Mean Square Effect	PVDF	=	Polyvinylidene Fluoride
MS_{error}	=	Mean Square Error	p	=	p-value
PPMS	=	Pneumatic Pressure Mandrel System	SOA	=	State of Art
			SS_{effect}	=	Sum of Squares effect
P_s	=	Pressure supplied	SS_{error}	=	Sum of Squares Error
PSI	=	Pounds per square inch	TCPS	=	Trash Compaction and Processing System
PU	=	Polyurethane			
PVC	=	Polyvinyl Chloride	W	=	PPMS weight

I. Introduction

MANAGING trash accumulation will be a significant challenge in human space exploration missions, whether in a spacecraft, space station, rover, or planetary surface. The accumulation of waste can influence crew efficiency, sanitation and hygiene, and launch cost. Since a certain volume on the spacecraft must be reserved for trash storage, trash accumulation contributes to the spacecraft's mass. Reducing trash volume is linked to a reduction in the overall mass, which leads to launch cost reductions.

Trash often takes up more space than its original form. Although the volume of some types of waste can be reduced through attempts to restore their original state, doing so can be labor-intensive for the crew, and can be impractical.

The current state-of-art (SOA) for trash compaction within NASA is the trash "football".[1] It is a hand compacted bag of trash wrapped with duct tape to retain its compacted form. Although the "football" reduces the volume of trash, it only compacts the trash to nominally 160kg/m3 and requires the use of a "larger than desired" quantity of tape. In addition to trash "footballs", Sierra Space is developing the Trash Compaction and Processing System (TCPS) with funding from NASA. [2] The TCPS uses pressure and heat to compact the trash and recover water resulting in microbial stabilization and safening, processes the gas effluents so it isn't released into the cabin, and finally, produce a compact rigid tile.

The TCPS's greater functionalities also entail a greater Equivalent System Mass (ESM). For scenarios where the TCPS's mass, power, or volume is in excess of the mission's limitations, a lower ESM system is required. That system is the Mechanical Trash Compactor (Mpactor). The Mpactor's lower ESM is produced by forgoing the heating which produces the water recovery and microbial safening. However, the Mpactor still produces an equivalent trash volume reduction as the TCPS.

The Mpactor was originally a compactor developed for the NASA Constellation Program and was called the Crew Exploration Vehicle (CEV) Compactor. The CEV Compactor was designed to only require two compactor bags per mission since the original trash model was less than the current trash model. Therefore, the original high-ESM design of the bags for the CEV missions must be eliminated and be replaced with lower-ESM, foldable materials to accommodate the development of the Mpactor.

This paper details the assembly and testing of the Pneumatic Pressure Mandrel System (PPMS), which mimics the normal force which the trash would exert on the Mpactor's compaction chamber sidewalls. By investigating the force required to remove a simulated bag from the trash chamber, this paper seeks to determine the best materials for the trash bag construction. While the Mpactor was undergoing upgraded in its engineering and control systems, the PPMS was built to collect preliminary data to mimic the force required to remove a fill trash bag from the Mpactor.

II. System Design

The PPMS contains two major sub-assemblies: The Poylmer-Sleeve Frame and the Pressurization Box. Figure 1 shows the assembly of the Poylmer-Sleeve Frame. The polymer film simulates the trash bag material being tested, and this film is folded into a sleeve. The frame is assembled using a series of stainless-steel tubing and tubing connectors. A hand-held heat sealer is used to fuse the overlapping edges of the polymer material. This framework allows for various polymer materials to be tested with an even distribution of removal force around the PPMS.

Figure 2 shows the construction of the Pressurization Box subassembly. In this subassembly, the two aluminum boxes have outer dimensions as 7.875" x 6.5" x 2", and each is made of 0.125" thick aluminum. The purpose of these boxes is to help transfer the force exerted from the pressurized inner tubes outward to the chamber side walls. The separator is 3D printed and placed between the rims to hold them in alignment, and the dimensions of it is 2.9" in outer diameter, 0.237" in thickness, and 0.8" in height. Two 5.5" x 7" x 0.0625" steel sheets were inserted to the front and back of the aluminum boxes to keep the inner tubes constrained during pressurization. The two sheets were slightly bent to allow for easier assembly of the construct.

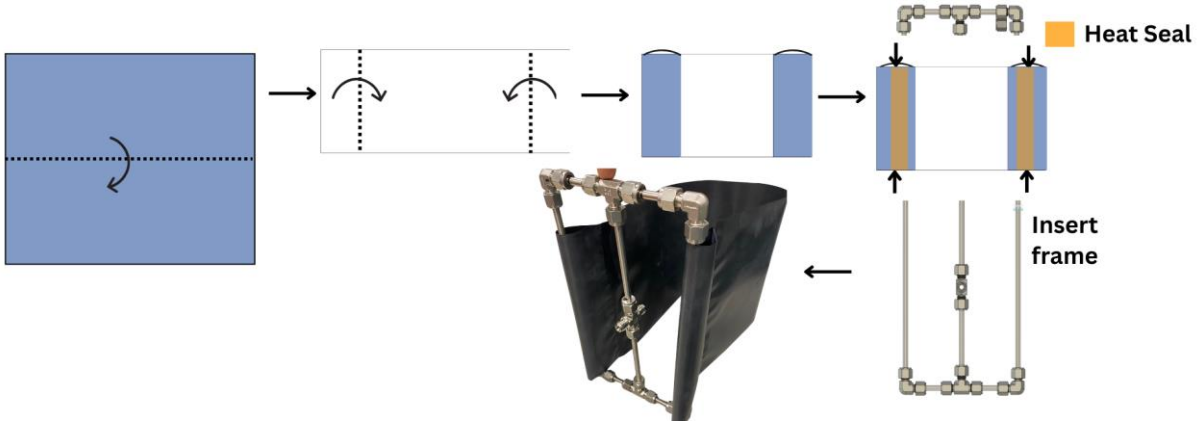


Figure 1. Process of assembling the Polymer-Sleeve Frame. The film is first folded to form a bilayer. Then, roughly 3 inches on each of its two sides are folded inwards and heat sealed to form two loops, allowing the insertion of the frame.

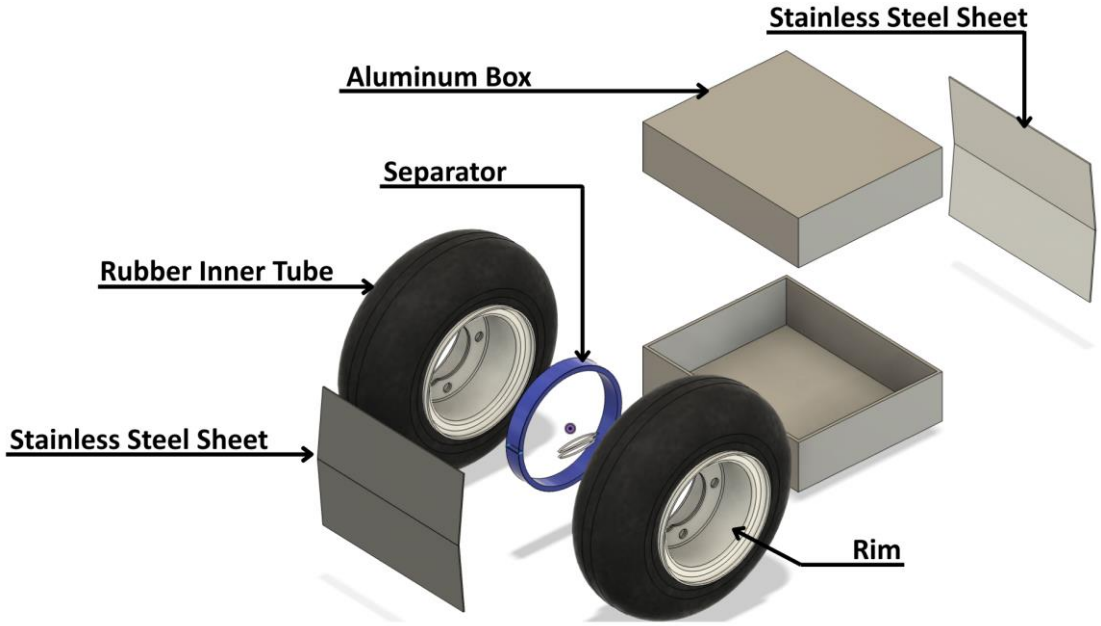


Figure 2. Process of assembling the Pressurization Box.

To simulate the lateral pressure that trash exerts on chamber side walls, the two rubber inner tubes (Figure 3) are connected to a pneumatic air compressor (Figure 4) using reinforced tubing and hose clamps. A 0–5 psi pressure gauge was used to read the pressure within the inner tubes, a second gauge was used as a plug for the 4th arm of the cross, and the "extra" tubbing and components over the pump were legacy from a prior application. The coarse metering valve was used to slow the rate of pressure increase within the PPMS. The PPMS was pressurized to nominally 1 psi over the target pressure and then the excess pressure was slowly bled off. It was later found that there was a pressure leak, likely due to backflow through the pump. Therefore, a ball valve was added right after the Compressor to effectively isolate the pressure gauges and PPMS from the Compressor.

The force gauge was zeroed and then connected to the Wrap-around Frame. A perpendicular removal force was applied at an increasing rate of nominally 0.5lb/second until the PPMS began to move. Then the removal force was

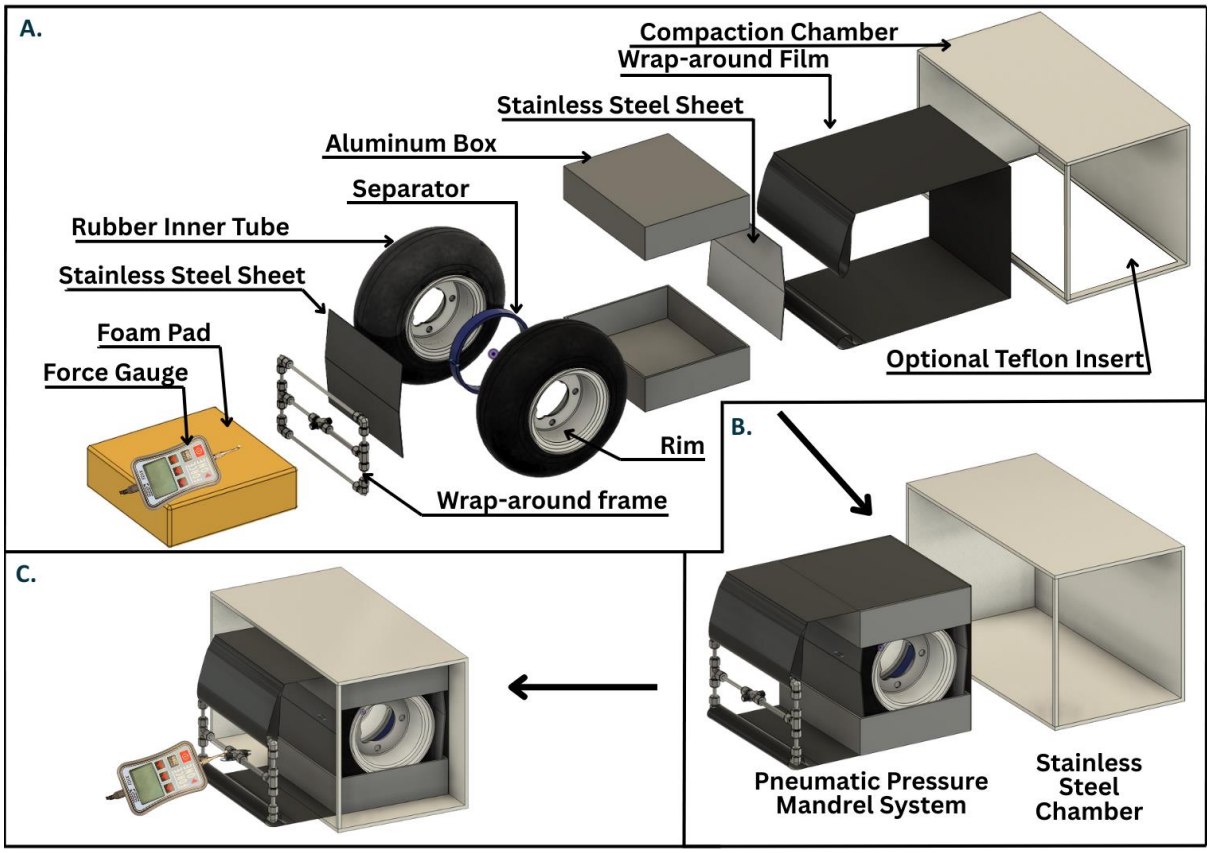


Figure 3. Assembly of Pneumatic Pressure Mandrel System (PPMS) and the chamber. A. Exploded view of the PPMS, the force-gauge/foam-pad, and compaction chamber. B. Insertion of the PPMS into the compaction chamber. C. Overall assembly with force gauge attached.

held constant to effect the constant slow removal of the PPMS. The initial and continuous removal forces were recorded. Finally, the PPMS was depressurized, reinserted into the compaction chamber, and the process repeated.

The authors acknowledge that the PPMS will not completely mimic a trash loaded bag, which will most likely have great variability in the special distribution of forces, but the PPMS will allow for a repeatable application of force upon which to compare and contrast the various polymeric films and their respective removal force. This data will allow for the elimination of materials that would produce a high remove force.

The NASA-STD-3001 Spaceflight Human-System Standard lists the allowable arm pull force for various operations based upon their criticality.[3] Table 1 shows those values. Based upon the definition of the various criticalities, the trash bag removal should be classified as "Other Ops" with a maximum arm pull force of 24 lb_f. To measure the arm pull force required,

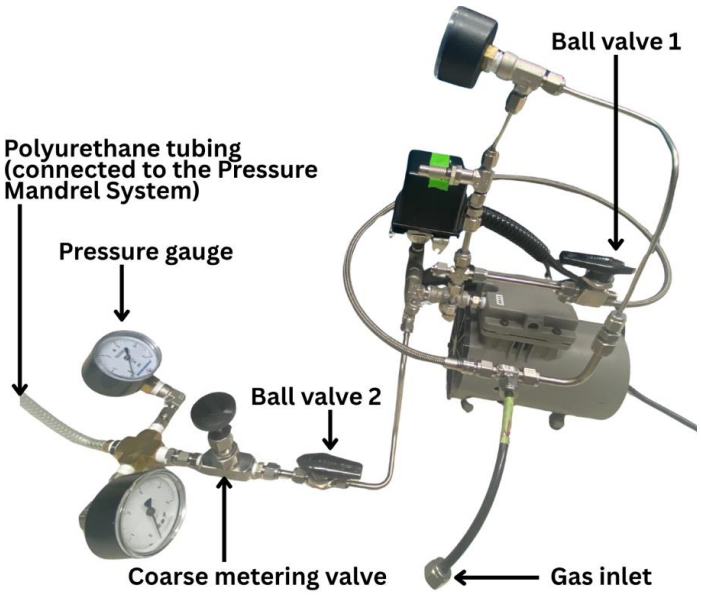


Figure 4. Compressor setup.

a force meter with a 70 lb_f maximum was used to measure the removal force at different sidewall normal forces which may be exerted by the trash. The sidewall normal force was calculated using the property force = pressure times contact area, the pressure supplied to the inner tubes, the contact area between the inner tubes and the inner wall of the aluminum boxes, and the mass in lb of the Pressurization Box.

Table 1. Crew Operational Loads for Arm Pulling

	Crew Operational Loads (lb_f)		
	Critical 1 Ops^	Critical 2 Ops*	Other Ops#
Arm Pull	10	13	24

^Criticality 1 Ops are tasks that involve the possibility of a single failure causing loss of life or vehicle.
***Criticality 2 Ops are tasks involving Loss of Mission alone.**
#Other Ops are all other tasks.

III. Data Collection

Several potential bag materials were investigated include black-dyed polypropylene (b.PP), polyvinylidene fluoride (PVDF, including both a rough and smooth surface), polyvinyl chloride (PVC), polyurethane (PU), clear polypropylene (c.PP), and an unidentified ethylene acrylate - low density polyethylene (EA-LDPE) copolymer. They were chosen for their different properties including heat sealing, elastomeric, rip tolerance, foldability, and flexibility. In a first round of testing, they were tested against the stainless steel wall of the compaction chamber. In a second round of testing, Teflon sheets were added to the compaction chamber sidewalls as shown in Figure 3a using double-sided tape assuming that the Teflon would greatly reduce the required removal force. The primary testing range was over the 0.5 – 2.0 psi range. This range was initially selected as pressures over 2 psi maxed out the force meter being used and pressures below 0.5 psi were difficult to measure with the initial 15 psi pressure gauge used for preliminary testing. However, a couple of the materials had a high removal force even at 0.5 psi, so those materials were tested over the 0.2 – 0.5 psi range. Since most of the collected Teflon data was less than 24 lb_f to remove the PPMS from the compaction chamber, the sidewall normal force required to produce a 24 lb_f was calculated (Table 2) and a final data point was collected. The result of this testing is presented in Figure 5. For the PU wrap-around film, beyond 70 lb_f of force was needed to pull the PPMS out of the compaction chamber, even at 0.2 psi. Thus, it wasn't possible to conduct pull-out experiments with PU. PVC was also difficult to remove requiring nearly 70 lb_f at a 1 psi pressure. Therefore, the PVC wrap-around film was tested at pressures of 0.2, 0.3, 0.4, and 0.5 psi. The rest of the materials were tested over the 0.5 – 2.0 psi range and were removable with less than 60 lb_f removal force. The best performing materials with a 24 lb_f removal force at a nominal 1.5 psi sidewall normal force were the b.PP and both the smooth and rough PVDF.

Table 2. Extrapolated Pressure for a 24 lb_f Removal Force^

Material Type	Pressure Supplied
Black PP	2.64 psi
PVDF Smooth	4.17 psi
PVDF Rough	2.66 psi
PVC	4.99 psi
PU	0.55 psi
EA LDPE	4.92 psi
Clear PP	4.42 psi

^ Estimated pressure required for a removal force of 24 lb_f. Value is extrapolated using the least squares regression equations computed for each material.

With the addition of Teflon to the compaction chamber sidewalls, all the materials performed better. The PU had its removal force reduced by greater than 50% with a removal force less than 24 lb_f at 0.5 psi and less. The PVC had its removal force reduced making it one of the best performing materials. The b.PP and rough PVDF both increased in performance, but not quite as good as the best performing materials. The best performing materials are PVC, EA-LDPE, c.PP, and smooth PVDF with a 24 lb_f removal force of just under 5 psi.

The following derivations were done to interpret the line of best fit. The coefficient of static friction, μ_s, is formally defined in physics as the ratio of the maximum static friction force f_s to the normal force N.[4]
This ratio can be rearranged to the following:

$$f_s = \mu_s N \qquad (A-1)$$

In this study, the normal forces are generated by pressure of the inner tubes acting on an area—pushing against the aluminum boxes' inner walls, which in turn pushes against the polymer material, which pushes against the

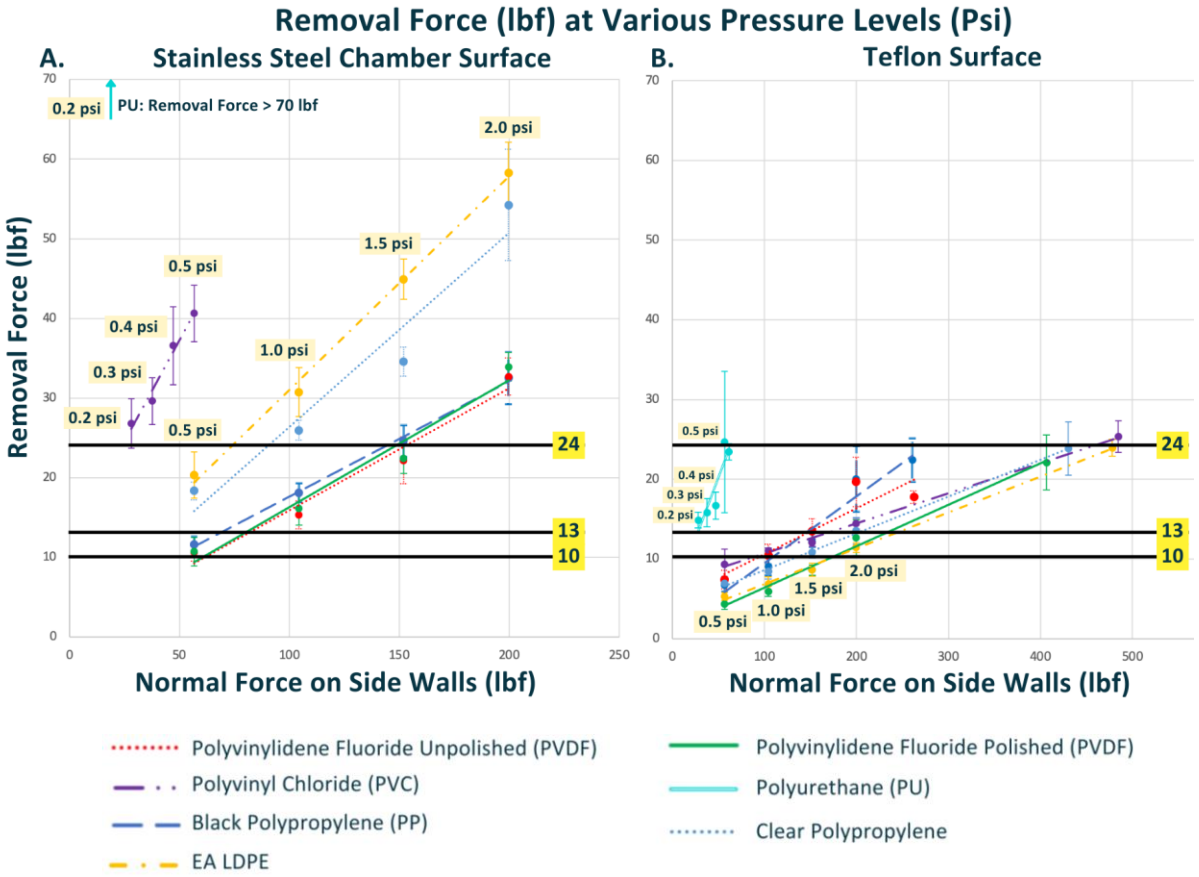


Figure 5. Force needed to remove the Pneumatic Pressure Mandrel System (lb_f) when the inner tubes are supplied with various pressure levels (psi). It was not possible to conduct removal force testing for Polyurethane, since even at 0.2 psi (the minimum pressure the pressure gauge can read), the force to remove the PU wrap-around was over 70lb (the limit the force gauge can measure). The lines 10, 13, and 24 are the critical 1, critical 2, and other operations, which are the limits to the force in lb for various crew operations in microgravity, as indicated by NASA (ref 4). A. When Teflon inserts were not added. B. When two pieces of Teflon inserts were added.

compaction chamber's walls, and the weight of the Pressurization Box. Pascal's Law states that pressure applied to an enclosed fluid is transmitted undiminished to all parts of the fluid and to the walls of the container. This law can be expressed as F = PA, where F is force, P is pressure, and A is area. Therefore, the following two equations can be obtained using variables defined in Table 3.

$$F_{N1} = P_s \times A_1 \qquad (A-2)$$

$$F_{N2} = (P_s \times A_2) + W \qquad (A-3)$$

By substituting the normal forces on the chamber's top and bottom walls in Eq. (A-2) and Eq. (A-3) into Eq. (A-1), the following equations can be obtained:

$$f_1 = \mu_s(P_s A_1) \qquad (A-4)$$

$$f_2 = \mu_s(P_s A_2 + W) \qquad (A-5)$$

Adding Eq. (A-4) and Eq. (A-5) obtains the following total removal force needed to be exerted:

$$F_R = f_1 + f_2 = \mu_s(2P_s A_T + W) \quad (A-6)$$

By matching Eq. (A-6) to Eq. (A-1), it can be concluded that the slopes of the lines of best fit for each material, either in contact with the Teflon insert or in contact with the compaction chamber's stainless-steel walls, represents μ_s, the coefficient of static friction for each material. The final equation used to interpret the lines of best fits for every line in Figure 5 is as follows:

$$F_R = \mu_s(2P_s A_T + W) \quad (A-7)$$

Table 3. Variables in the Line of Best Fit Reference Equation and Their Definitions

Variable	Definition
$2P_s A_T + W$	Normal force on chamber side walls (lb_f)
μ_s	Coefficient of static friction
A_T	Total inner wall area of the box (the contact area between the rubber inner tubes and the box) (in^2) $A_T = A_1 + A_2 = 6.25 \times 7.625 = 47.656$ in^2
A_1	Inner wall area of the top aluminum box (the contact area between the rubber inner tubes and the top box) (in^2)
A_2	Inner wall area of the bottom aluminum box (the contact area between the rubber inner tubes and the bottom box) (in^2)
F_R	Removal force (lb_f)
F_{N1}	Normal force exerted on the compaction chamber's top wall
F_{N2}	Normal force exerted on the compaction chamber's bottom wall
f_1	Static friction between inner tubes and chamber top wall
f_2	Static friction between inner tubes and chamber bottom wall
P_s	Pressure supplied to the inner tubes by the compressor (psi)
W	PPMS weight (2x of rim, aluminum box, steel sheet, rubber inner tube, and 1 separator) (lb_f) $W = 8.99$ lb

IV. Statistical Analysis

A three-factor mixed-design ANOVA was conducted, with one between-subjects factor (the material type), two within-subject factors (surface type and pressure level), and the dependent variable being the minimum force exerted to pull the PPMS out. This is chosen instead of a normal ANOVA because each wrap-around film, which was made of a specific material, was repeatedly tested across four pressure levels, and tested for both when Teflon inserts were added and not added to the compaction chamber. In a regular ANOVA, when the dependent variable (removal force) is measured multiple times for the same unit, the assumption of independent measurement errors is violated. By using a mixed-design ANOVA, the within-subject effects caused by Teflon addition is analyzed separately from the between subject effects caused by material of the wrap-around film. In other words, mixed ANOVA controls for the baseline differences between materials to explicitly test the within-subject effects, and this is done by comparing each material to itself when testing for the factors Teflon and pressure. By canceling out the baseline differences, the mixed design ANOVA reduces the error variance, and therefore has greater statistical power. The variables used for the analysis can be found in Table 4.

The polyurethane group was omitted from the ANOVA because ANOVA requires at least one valid observation per group to compute variance, and no data could be collected for the polyurethane without Teflon group. The PVC group was also omitted, because without Teflon, the removal force for PVC could only be measured at pressure ranges 0.2psi – 0.5psi due to the removal force at pressures over 0.5psi being beyond the measurable range of the force gauge. Therefore, these two materials are only reported qualitatively.

Table 4. Variables Used in the Statistical Analysis Calculations and Their Definitions

Variable	Definition
$\eta^2{}_p$	Partial eta squared, which is an effect size representing the proportion of the total variance in the dependent variable that is explained by an independent variable, while controlling for the influence of all other independent variables and interactions in the model.
F	F-statistic, which is the ratio of the variance between groups to the variance within groups
p	p-value, which is the probability of obtaining data at least as extreme as the observed data, assuming that the null hypothesis (there is no effect or difference between experimental groups) is true. A p-value < 0.05 indicates that there is a significant difference between experimental groups.
df	Degrees of freedom, which is the number of independent values that can vary in an analysis.
df_{error}	Degrees of freedom for the error term.
SS_{effect}	Sum of Squares of an effect, which is a measurement of the variation in the dependent variable that is accounted for by a specific effect
SS_{error}	Sum of Squares Error, which represents the variability within groups (the amount of unexplained variation)
MS_{effect}	Mean Square, obtained by dividing a sum of squares (the SS_{effect}) by its corresponding degrees of freedom. Quantifies the average variation between groups.
MS_{error}	Mean Square, obtained by dividing a sum of squares (the SS_{error}) by its corresponding degrees of freedom. Quantifies the average variation within groups.

There was a significant interaction between the between-subject and within-subject factors. The interaction between surface type and material has an effect size of partial $\eta^2 = 0.973$ (Table 5). The material type factor has an effect size of partial $\eta^2 = 0.931$ (Table 6), which indicates statistical significance between different material groups. Therefore, downstream analysis must be conducted to isolate the predictors by levels to better understand the nature of the interactions.

Table 5. Three-Factor Repeated Measures ANOVA (Analysis of Variance), Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η_p^2
Surface Type	42550.159	1	42550.159	8044.011	< .001	0.991
Surface Type ∗ Material	14641.692	4	3660.423	691.995	< .001	0.973
Residuals	407.305	77	5.290			
Pressure Level	29259.417[a]	3[a]	9753.139[a]	2036.851[a]	< .001[a]	0.964
Pressure Level ∗ Material	822.000[a]	12[a]	68.500[a]	14.306[a]	< .001[a]	0.426
Residuals	1106.107	231	4.788			
Surface Type ∗ Pressure Level	7243.081[a]	3[a]	2414.360[a]	622.058[a]	< .001[a]	0.890
Surface Type ∗ Pressure Level ∗ Material	2732.898[a]	12[a]	227.742[a]	58.677[a]	< .001[a]	0.753
Residuals	896.568	231	3.881			

Note. Type III Sum of Squares

Table 6. Three-Factor Repeated Measures ANOVA (Analysis of Variance), Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η_p^2
Material	8310.939	4	2077.735	257.868	< .001	0.931
Residuals	620.417	77	8.057			

Note. Type III Sum of Squares

Simple effects are defined as the effect of variable A on the dependent variable, when variable A is restricted only to a specific level of some other variable B. Since the interaction effect between Teflon presence, the material type,

and the pressure level is statistically significant ($p < 0.001$), simple main effects analyses were conducted to explore the nature of the interaction (Table 7 and Table 8).

Table 7. Simple Main Effects Analysis (Effects of Material Isolated by Teflon Presence and Pressure Level)

Level of Surface Type	Level of Pressure Level	Sum of Squares	df	Mean Square	F	p
Stainless Steel	0.5	1576.103	4	394.026	48.903	< .001
	1	3531.924	4	882.981	109.587	< .001
	1.5	7871.882	4	1967.971	244.245	< .001
	2	11825.869	4	2956.467	366.927	< .001
Teflon	0.5	95.843	4	23.961	2.974	0.024
	1	185.549	4	46.387	5.757	< .001
	1.5	313.927	4	78.482	9.740	< .001
	2	1106.432	4	276.608	34.330	< .001

Note. Type III Sum of Squares

Table 8. Simple Main Effects Analysis (Effects of Material Isolated by Pressure Level)

Level of Surface Type	Sum of Squares	df	Mean Square	F	p
Stainless Steel	21678.274	4	5419.568	672.623	< .001
Teflon	1274.357	4	318.589	39.540	< .001

Note. Type III Sum of Squares

In both types of surfaces, and in all levels of pressure supplied, there is a statistically significant difference in the removal force needed between the different types of material used in the wrap-around film. To quantify the proportion of variance in the removal force that is explained by the variable "material type", calculations of partial η^2 was then done. The partial η^2 calculation equation (B-1) was developed by Jacob Cohen.[5] The relationship SS = MS * df (Equation B-2) and the F-statistic = the variance ratio (Equation B-3) was developed by statistician Ronald Fisher during his development of ANOVA.

$$\text{partial } \eta^2 = \frac{SS_{effect}}{SS_{effect} + SS_{error}} \quad (B-1)$$

$$SS_{error} = MS_{error} \times df_{error} \quad (B-2)$$

$$F = \frac{MS_{effect}}{MS_{error}} \quad (B-3)$$

For the Stainless Steel surface, the values from Table 7, the simple main effects analysis, are used for equations B-4 and B-5. The Sum of Squares and Mean Square values from Table 5, the overall ANOVA, were not used for these equations because they reflect the overall surface type variable's influence on the removal force, rather than separating the surface type into the two levels. Furthermore, since there are statistically significant interaction effects between variables as shown in Table 5, the output from the simple main effects analysis must be looked at instead, which breaks down the variable by its levels.

$$SS_{effect} = 21678.274 \quad (B-4)$$

$$MS_{effect} = 5419.568 \quad (B-5)$$

Since partial η^2 looks at the proportion of variance explained by the different material types (the between-subjects factor), when calculating the SS_{error} term, the corresponding mean square of residuals and degrees of freedom of residuals must also come from the between-subjects analysis in ANOVA. Therefore, values from Table 6 are used in the following equations (B 6-8).

$$df_{error} = 77 \quad (B-6)$$

$$MS_{error} = \frac{MS_{effect}}{F} = \frac{5419.568}{672.623} = 8.057 \quad (B-7)$$

$$SS_{error} = 8.057 \times 77 = 620.389 \quad (B-8)$$

$$\text{partial } \eta^2 = \frac{21678.274}{21678.274 + 620.389} = 0.972 \quad (B-9)$$

$$\text{partial } \eta^2 = 0.972 \quad (B-10)$$

Similar to the explanations provided above, for the Teflon surface, the values from Table 7 are used for equations B-11 and B-12. The residual's statistics from Table 6 between-subjects analysis are used for equations B-13, B-14, and B-15.

$$SS_{effect} = 1274.357 \quad (B-11)$$

$$MS_{effect} = 318.589 \quad (B-12)$$

$$df_{error} = 77 \quad (B-13)$$

$$MS_{error} = \frac{MS_{effect}}{F} = \frac{318.589}{39.540} = 8.057 \quad (B-14)$$

$$SS_{error} = 8.057 \times 77 = 620.389 \quad (B-15)$$

$$\text{partial } \eta^2 = \frac{1274.357}{1274.357 + 318.589} = 0.800 \quad (B-16)$$

$$\text{partial } \eta^2 = 0.800 \quad (B-17)$$

When Teflon was not added, there was a significant effect of material type on the removal force exerted, with partial $\eta^2 = 0.972$. Partial η^2 is a measure of effect size, showing how much of the variation in the outcome being measured is explained by the factor being tested. Table 9 show the established benchmarks on interpreting its value. In this case, 97.2% of the variance in the removal force was due to the difference in materials. When Teflon was added, the material type still had a significant effect, though this effect was smaller, with partial $\eta^2 = 0.800$. This indicates that 80% of the variance in force can be attributed to material differences.

Table 9. Effect Size Benchmarks*

Partial η^2	Effect Size
0.01	Small Effect
0.06	Moderate Effect
≥ 0.14	Large Effect

*Benchmarks are set by Cohen (1988).[6]

Holm post hoc correction comparisons (Table 10) for the interaction was also done to further understand how material differences and surface types can influence the removal force. PU and PVC were excluded from this analysis since their removal force was significantly higher, i.e., to high to collect data over the 0.5 – 2.0 psi range. When the surface was stainless steel, the removal force needed was significantly higher in EA LDPE than the other four materials (t=33.037, $p_{holm}<0.001$; t=30.554, $p_{holm}<0.001$; t=33.168, $p_{holm}<0.001$; t=9.861, $p_{holm}<0.001$). The removal force needed for clear polypropylene was significantly higher than PVDF Smooth, Black Polypropylene, and PVDF Rough (t=-20.071, $p_{holm}<0.001$; t=-18.244, $p_{holm}<0.001$; t=-20.521, $p_{holm}<0.001$). Here, the negative t-values reflect the direction of subtraction in the statistical test. If each of the three materials (PVDF Smooth, Black PP, and PVDF Rough) are called Material A, then the comparisons were conducted using (Material A's removal force – Clear PP's removal force). The negative signs in the t-values and the mean difference indicate that the removal force values for Clear PP is much greater than the removal force produced by these three materials.

With Teflon added, EA LDPE showed a significantly lower removal force needed than Black Polypropylene, PVDF Rough, and Clear Polypropylene (t=-14.861, $p_{holm}<0.001$; t=-17.518, $p_{holm}<0.001$; t=-7.019, $p_{holm}<0.001$).

Table 10. Holm Post Hoc Comparisons – Material × Surface Type – Conditional on Surface Type

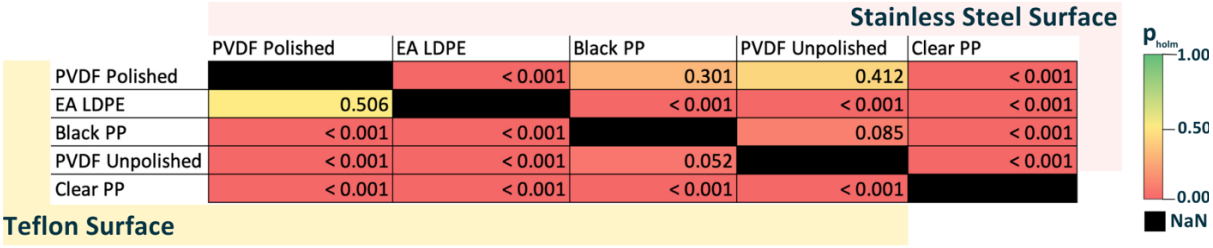
Surface Type			Mean Difference	SE	df	t	p_{holm}
Stainless Steel	EA, LDPE	PVDF, Polished	17.739	0.537	77	33.037	< .001***
		Black, Polypropylene	16.822	0.551	77	30.554	< .001***
		PVDF, Unpolished	18.261	0.551	77	33.168	< .001***
		Clear, PP	5.295	0.537	77	9.861	< .001***
	PVDF, Polished	Black, Polypropylene	−0.918	0.632	77	−1.452	0.301
		PVDF, Unpolished	0.521	0.632	77	0.825	0.412
		Clear, PP	−12.444	0.620	77	−20.071	< .001***
	Black, Polypropylene	PVDF, Unpolished	1.439	0.643	77	2.237	0.085
		Clear, PP	−11.527	0.632	77	−18.244	< .001***
	PVDF, Unpolished	Clear, PP	−12.966	0.632	77	−20.521	< .001***
Teflon	EA, LDPE	PVDF, Polished	0.176	0.263	77	0.669	0.506
		Black, Polypropylene	−4.008	0.270	77	−14.861	< .001***
		PVDF, Unpolished	−4.725	0.270	77	−17.518	< .001***
		Clear, PP	−1.846	0.263	77	−7.019	< .001***
	PVDF, Polished	Black, Polypropylene	−4.184	0.310	77	−13.517	< .001***
		PVDF, Unpolished	−4.900	0.310	77	−15.832	< .001***
		Clear, PP	−2.022	0.304	77	−6.657	< .001***
	Black, Polypropylene	PVDF, Unpolished	−0.717	0.315	77	−2.273	0.052
		Clear, PP	2.162	0.310	77	6.984	< .001***
	PVDF, Unpolished	Clear, PP	2.878	0.310	77	9.299	< .001***

*** p < .001

Note. P-value adjusted for comparing a family of 10 estimates.

PVDF Smooth also showed a significantly lower removal force needed than the three materials previously listed (t=-13.517, p_{holm}<0.001; t=-15.832, p_{holm}<0.001; t=-6.657, p_{holm}<0.001). The removal force produced by Clear Polypropylene was significantly lower than Black Polypropylene and PVDF Rough (t=6.984, p_{holm}<0.001; t=9.299, p_{holm}<0.001). The p values comparing each pair of materials can be visualized in Table 11 above, and the removal force magnitude of each material can be visualized in figure 6 below.

Table 11. Heat Map Visualization of Statistically Significant Pairs from Holm Post Hoc Comparisons



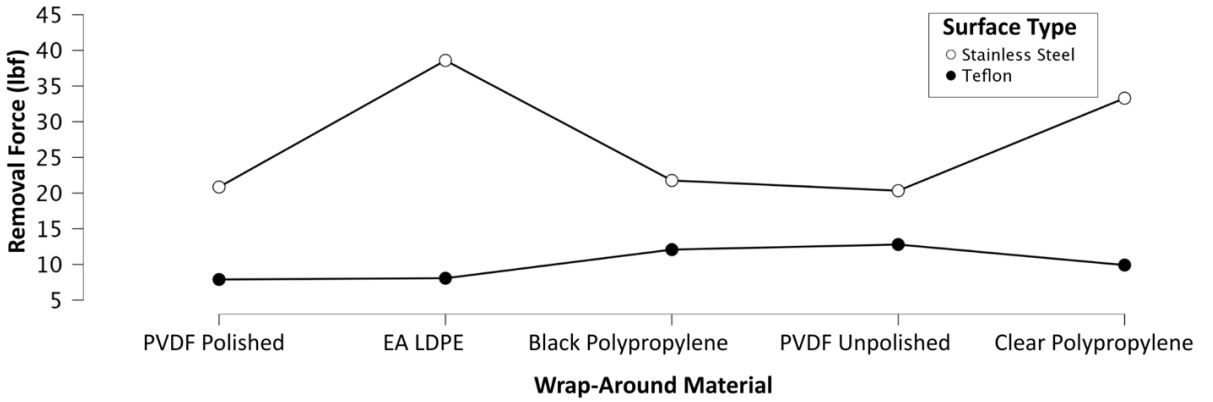


Figure 6: Removal force for wrap-around materials.

V. Conclusion

A short list of 7 polymeric materials were chosen as potential bag construction material based upon their general properties. These materials were tested in the PPMS to determine the ease of bag removal from the Mpactor compaction chamber. This testing identified the three best materials for use directly in the compaction chamber, i.e., directly against the native stainless steel wall, and four materials which performed even better when the Mpactor chamber walls were lined with Teflon. The four best materials, which all performed substantially similar to each other are EA-LDPE, PVC, smooth PVDF, and a clear PP.

From the NASA-STD-3001, Volume 2, Revision E, the trash bag should be removable with not more than a 24 lb_f arm pull. For the stainless steel surface, the three best performing materials met this limitation at only 1.5 psi of normal force. When the compaction chamber walls were lined with Teflon, the allowable sidewall normal force is increased to nominally 5 psi. It should be noted that the contact area for this testing was nominally 100 in^2 (50 in^2/sidewall), nominally the same contact area as the current Mpactor design fill up to the bottom of the front ring. It should be noted that, a different sized trash bag or distribution of normal force will change the magnitude of the results but the trends should remain constant.

It should be noted that going from the stainless steel to the Teflon chamber surface, all the materials performance improved, although, it should be noted that three materials performed different than expected. First, the EA-LDPE was not one of the three best performers for the stainless steel surface, although it is probably the best performed vs the Teflon surface. Second, the rough and smooth PVDF performed similarly vs the stainless steel surface, although the rough PVDF doesn't perform as well vs the Teflon. Finally, the performance of the two (black and clear) PP performed differently depending upon the chamber surface. The black PP was one of the best three materials vs the stainless steel while the clear PP was one of the best vs the Teflon.

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References

[1]Pace, G. S., and Fisher, J. W., "Compaction Technologies for near and far term space missions," SAE Technical Paper Series, Jul. 2006.

[2]Richardson, J. T., Sepka, S. A., Martin, K., Borrego, M. A., Ewert, M. K., White, D. W., Young, J. C., Pace, G. S., Trieu, S. S., and McKinley, M., "The Trash Compaction Processing System (TCPS) Technology Demonstrations and Risk Reduction Activities 2023-2024," NASA Available: https://techport.nasa.gov/projects/93127.

[3]"NASA spaceflight human-system standard volume 2: Human factors, habitability, and environmental health," NASA Available: https://standards.nasa.gov/standard/NASA/NASA-STD-3001_VOL_2.

[4]Boston University. (2023a). *Static friction*. Bu.edu. https://physics.bu.edu/~redner/211-sp06/class05/static.html

[5]Cohen, J. (1973). Eta-Squared and Partial Eta-Squared in Fixed Factor Anova Designs. *Educational and Psychological Measurement*, *33*(1), 107–112. https://doi.org/10.1177/001316447303300111

[6]Cohen, J., Statistical Power Analysis for the behavioral sciences, May 2013.