Comparative Life Cycle Assessment (LCA) of Protective Garments: Reusable vs. Disposable in Radioactive Material Applications – 14634

John Jewell[1], Maggie Wildnauer[1]
[1]PE INTERNATIONAL, Inc.

ABSTRACT

Protective garments, used to avoid low-level radioactive particulate contamination, can only be worn once before they must be decontaminated through either laundering or disposal. While both reusable garments and disposable garments can provide this function, which is better for the environment? Considering a functional unit of one wearing event, the reusable garment impacts are allocated across the number of possible lifetime uses. Single use garments from OREX®[a] are made from Polyvinyl Alcohol (PVOH) and dissolved after use. After only four uses, the reusable product already has less impact than the disposable alternative. Data from UniTech, a radiological laundering service provider and commissioner of this study, showed that 48 uses was a more representative value for lifetime uses – reducing the impact of one wearing event of the reusable garment to 0.78 kg CO_2e/use, less than one-fifth the impact of the disposable (10.4 kg CO_2e/use). This conclusion is markedly different than a previous LCA by Eden which compared these products, mainly because the Eden study incorrectly modeled PVOH with its precursor polyvinyl acetate (PVAc), neglecting the energy intense hydrolysis process.

INTRODUCTION

Goal

The goal of the study is to compare the cradle-to-grave environmental performance of a reusable protective garment set with a disposable alternative. The study will be used by marketing, R&D, facilities management, and executives within UniTech. Externally, UniTech will communicate the results to current and potential customers through marketing initiatives. Since this report will be used to support and reinforce any marketing assertions, a third-party critical panel review has been performed to confirm that the LCA fulfills the requirements of the ISO 14040/44 standards.

Scope

This study evaluates two types of protective garments, reusable and disposable, used to prevent low-level radioactive particulate contamination. These suits are primarily required when nuclear power plants undergo maintenance activity during shutdown periods. An entire set of garments includes coverall, hood, shoe covers, rubber shoes, rubber gloves, and one set of scrubs. To evaluate a functional unit of one wearing event, the disposable set is produced once and the reusable set is allocated across its lifetime uses. Number of uses calculated to be greater than 200 were rounded down to 200 for a conservative assessment, shown in Table I below. The scope of the study includes manufacturing, laundering, and End-of-Life (EoL) treatment, along with the associated transport in and between phases. Primary data are representative of the UniTech fiscal year, September 2011 through August 2012. Secondary data are taken from a

[a] OREX is a registered trademark of OREX Incorporation in the United States

range of sources. Background data necessary to model material production, energy use, etc. was adopted from PE INTERNATIONAL's GaBi 2012 database.

The region under study for the use phase is the United States. Manufacturing of the fabric components of the disposable garment and portions of the reusable garment set occurs in China, with the remaining reusable garment fabric manufacturing occurring in the United States. Rubber shoes and gloves are manufactured in Taiwan and China, respectively, for both garment sets.

Environmental impacts were calculated using TRACI 2.1 including Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Smog Creation Potential (Smog). Primary Energy Demand (PED) and Water Consumption (Water) were also calculated.

TABLE I. Reference flows

Type	Weight of Reusable Garments (*lbs*)	Lifetime Uses	Reusable garment weight scaled by lifetime uses (*lbs*)	Weight of Disposable Garments (*lbs*)
Coverall	1.05	48	2.19E-02	0.67
Hood	0.21	200	1.05E-03	0.07
Shoe covers	0.25	88	2.84E-03	0.13
Shoes	0.53	23	2.30E-02	0.29
Gloves	0.27	9	3.00E-02	0.15
Scrub Top	0.41	200	2.05E-03	0.24
Scrub Bottom	0.38	200	1.90E-03	0.23
Laundry bag	1.47	140	1.05E-02	-

DESCRIPTION

Life Cycle Inventory Analysis - Reusable

The lifecycle of the reusable garment set begins with the manufacturing of each component. The garment set is made from ProTech[b], CoolTech[c], Rubber, Nylon, and polyvinyl chloride in Asia and North America. The garment sets are then transported to UniTech's distribution facility before being sent to the customer

After use, the reusable garment set is placed in the provided laundry bag and trucked to the closest UniTech laundering facility. All items, including the laundry bag, are then washed, dried, and tested for persisting radiological contamination. If unacceptable levels of contamination are found, the garment is either re-washed or landfilled in an appropriate facility.

TABLE II. UniTech laundering requirements

Type	Flow	Amount	Unit	Source	Distance	Unit	Mode

[b] Nylon fabric with antistatic properties
[c] Polyethylene Terephthalate (PET) fabric with antistatic properties

Input	Garment	1.00	lbs	Calculated	320	mi	Class 5 truck
	Electricity	0.51	kWh	Calculated	n/a		
	Natural Gas	0.05	therms	Calculated	n/a		
	Water	4.56	gal	Calculated	n/a		
	Laundry Chemicals	1.13	oz	Calculated	Excluded		
Output	Garment	1.00	lbs	Calculated	320	mi	Class 5 truck
	Wastewater	3.64	gal	Calculated	n/a		

Primary data from UniTech facilities was used to calculate the laundering requirements per pound of material processed, including both washing and drying activities, shown in Table II above.

Low-level radioactive waste in the United States is generally landfilled in sealed containers, a process also followed by UniTech. EoL is modeled as landfill of inert material so there is no energy credit from landfill gas. The waste is transported an average of 1,150 miles by truck.

Life Cycle Inventory Analysis - Disposable

The disposable garment under consideration in this study is a hot-water soluble, Polyvinyl Alcohol (PVOH) based material used for all fabric applications (i.e., coverall, hood, shoe covers, and scrub set). The shoes and gloves are both made of rubber. The lifecycle of the disposable garment set consists of initial garment manufacturing, the wearing event, dissolution of the PVOH material, and final incineration of any un-dissolved components. Transportation in and between stages is also included.

TABLE III. Dissolution process for PVOH material

Type	Flow	Magnitude	Unit
Inputs	PVOH Garment	1.00	lbs
	Natural Gas	4,550	Btu
	Water	5.28	gal
	H_2O_2	0.37	lbs
	$FeSO_4$	0.002	lbs
Outputs	Waste to incineration	0.06	lbs
	Wastewater	5.53	gal
	Carbon Dioxide (emission to air)	0.19	lbs

Data for the disposable garments was taken from publically available information describing OREX®, a participant in the market for this type of garments. The inputs and outputs are based on information on disposable garments obtained from a recent LCA conducted by Eden Nuclear and Environment [1].

After manufacturing and transport to a customer, the PVOH garment set is transported an average of 835 miles to be treated. The PVOH is dissolved and treated using a Fenton reaction ($FeSO_4 + H_2O_2$); amounts in Table III are from the Eden report and our assumption of 100% concentration H_2O_2 and the $FeSO_4$ at 0.5% of the H_2O_2.

DISCUSSION

Life Cycle Impact Assessment Results

The environmental impacts are broken down by life cycle stage for reusables in Figure 1 below. As expected, both material manufacturing and laundering contribute significantly to the total impact, while transportation has a much smaller impact and EoL treatment is negligible.

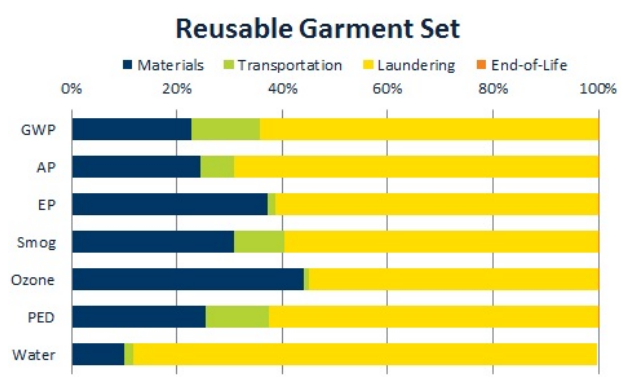

Fig. 1. Lifetime environmental impacts of the reusable garment set as a percent of total

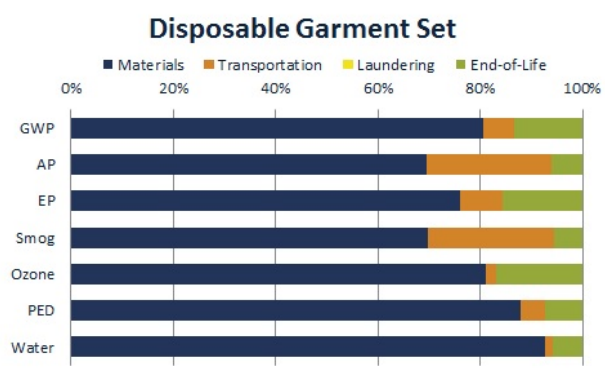

Fig. 2. : Lifetime environmental impacts of the disposable garment set as a percent of total

The environmental impacts are broken down by life cycle stage for disposables in Figure 2. For disposables, the impacts are overwhelmingly due to the manufacturing of the garment set. Additionally, both transportation and EoL processing, combined, contribute anywhere from 10-30% of lifetime impacts. The CO_2 emissions from the chemical reaction that occurs during dissolution of the disposable garment only contribute approximately 1% of the lifetime impact.

When comparing reusable vs. disposable for a single wearing event, the reusable garment set has significantly less environmental impact than the disposables for the following categories: Global Warming, Acidification, Smog, and Primary Energy Demand (19%, 27%, 17%, and 17% respectively) as shown in Figures 3 - 6. This result is overwhelmingly due to the production of PVOH during manufacturing.

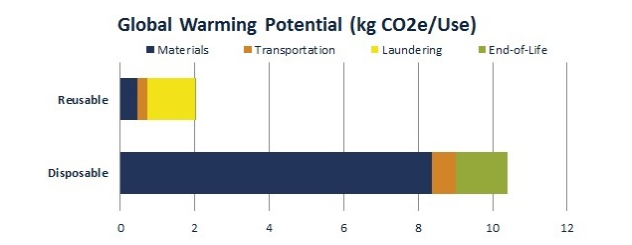

Fig. 3. Global warming potential per use

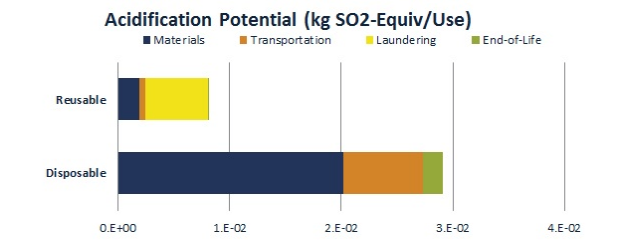

Fig. 4. Acidification potential per use

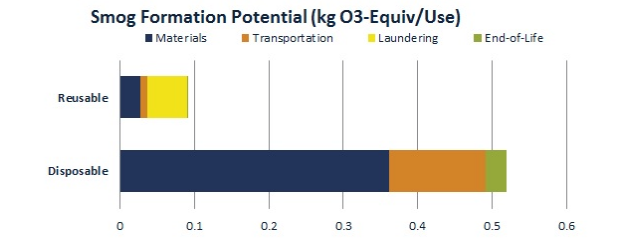

Fig. 5. Smog formation potential per use

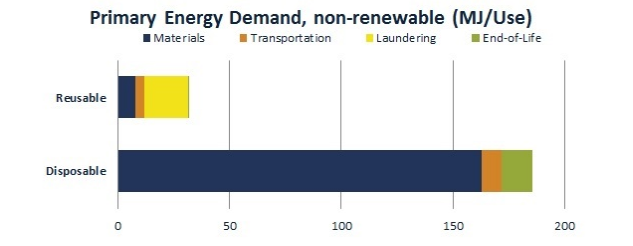

Fig. 6. Primary energy demand per use

Similarly, as shown in Figure 7 the reusable garment requires 60% less water than the disposable alternative. The water required during laundering of the reusable garment is less than that required to manufacture PVOH.

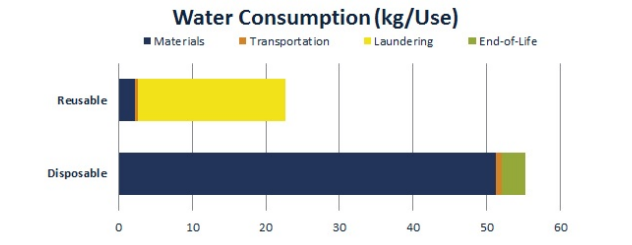

Fig. 7. Water consumption per use

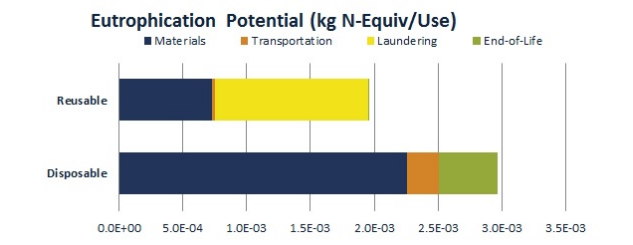

Fig. 8. Eutrophication Potential per use

The difference between reusable and disposable is much less significant when considering the Eutrophication Potential as shown in Figure 8. The reusable option's wastewater emissions contribute to EP, though not enough to outweigh production and dissolution of PVOH.

As shown in Figure 9, both the reusable and disposable garments render virtually the same Ozone Depletion Potential.

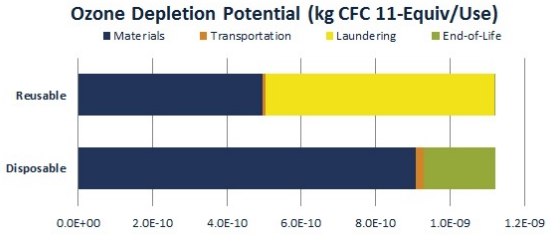

Fig. 9. Ozone depletion potential, per use

CONCLUSIONS

In summary, reusables' impacts are dominated by use phase washing and to a limited extent, raw materials. Disposables' impacts are driven by raw materials, followed by transportation.

Reusable protective garments have significantly lower impact than disposables in every impact considered except ODP. Though reusables have reduced environmental impact, improvements related to washing energy and water use would further minimize the burdens attributed to reusable garments.

A key factor in this comparison is the number of uses the reusable garment set can spread its burdens across. While UniTech records average lifetime washes of their garments using RFID tags, the values for the number of uses of a reusable garment are a potential source of debate. Therefore, a scenario analysis is used to test the robustness of the conclusions made in this study.

Figure 10 shows the baseline GWP for the disposable and reusable garment sets, along with three other scenarios for possible lifetime uses of the reusable garment. The lifetime uses of each component are described in Table IV.

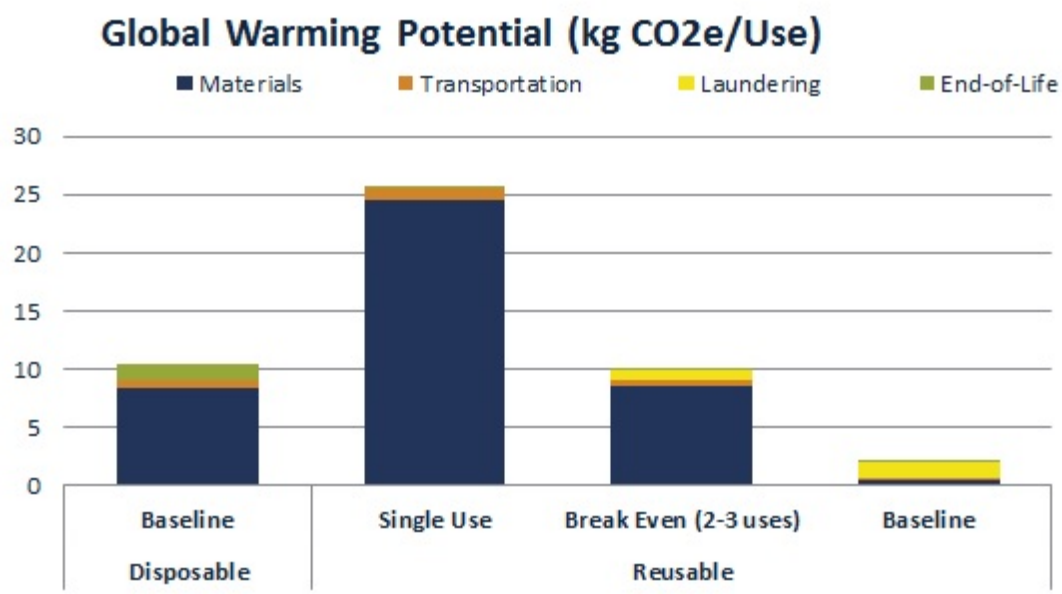

Fig. 10. GWP sensitivity results

TABLE IV. Lifetime use scenarios

	Single Use	Break Even	Baseline
Coverall	1	3	48
Gloves	1	2	9
Hood	1	3	200
Shoes	1	2	23
Shoe covers	1	3	88
Scrub Top	1	3	200
Scrub Bottom	1	3	200
Laundry bag	1	3	140

Varying the number of lifetime uses in a sensitivity analysis showed that reusables typically win after 4 uses, which is far below actual usage behavior.

It is also important to note that the results in this study show significant benefit for reusables, even more so than in other LCAs comparing reusables vs. disposables. For example, the main difference between these results and those in the study by Eden Nuclear and Environment [1] is the evaluation of PVOH production. Eden incorrectly used Polyvinyl Acetate (PVAc), a chemical precursor to PVOH, as a proxy for PVOH. According to the GaBi databases, PVAc has Global Warming Potential of about 2kg CO_2eq. / kg whereas PVOH (including hydrolysis) has 8.8 kg CO_2eq. / kg. The results are similar for other environmental impacts considered.

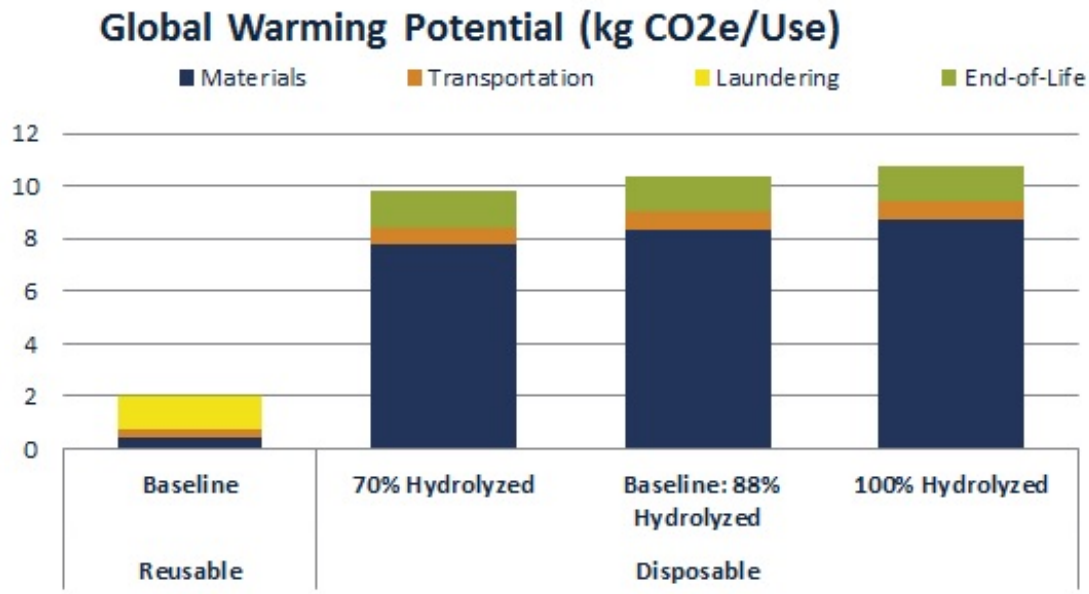

Fig. 11. Degree of hydrolysis scenario analysis

Additionally, there are multiple ways to produce a hot-water soluble PVOH garment. While the exact specification for individual garments is proprietary information, it was assumed to be made of partially-hydrolyzed PVOH based on existing patents for similar technology [2].

Existing literature shows that the degree of hydrolysis required can vary significantly. A search through U.S. patents yielded degrees of hydrolysis at 88% [2], 70-95% [3], and 98% [4]. Figure 11 shows how the total GWP of the disposable garment varies with degree of hydrolysis. While the value chosen does affect the total, it does not change the conclusion of this study, as the reusable garment still has a significantly lower impact.

REFERENCES

[1] EDEN, "Eden Nuclear and Environment, SKM Enviros: Quantifying the Carbon Footprint associated with OREX® and Textile Garment use in the USA," 2012. [Online]. Available: http://www.orex.com/wp-content/uploads/2010/09/Orex-Carbon-Footprint-report-USA-Final.pdf.

[2] X. YANG and R. J. PETCAVICH, "Hot water soluble disposable films, fabrics and articles". Patent U.S. Patent 5,658,977, 19 August 1997.

[3] J. D. LANGLEY, "Breathable polyvinyl alcohol protection wear". Patent U.S. Patent 5,869,293, 9 February 1999.

[4] T. W. HONEYCUTT, "Method of producing hot water soluble garments and like fabrics". Patent U.S. Patent 5,871,679, 16 February 1999.