Comparative assessment of wet and dry garment cleaning.
Part 1. Environmental and human health assessment

Gregory A. Keoleian,[1,*] Catherine E. Blackler,[1] Richard Denbow[2] and Ruth Polk[3]

[1]National Pollution Prevention Center, School of Natural Resources and Environment, University of Michigan, Dana Building, 430 E. University, Ann Arbor, MI 48109-1115, USA
[2]ICF Kaiser Inc., 9300 Lee Highway, Fairfax, VA 22031, USA
[3]Silent Spring, Inc., 29 Crafts Street, Newton, MA 02158, USA

Water-based cleaning of specialty garments is emerging as a potential alternative to dry cleaning. Perchloroethylene, the solvent used in dry cleaning, poses significant human and ecosystem health concerns. This paper is part 1 of a two part series that analyzes the key environmental, human health, performance, economic, and regulatory factors which influence the future of the garment cleaning industry. This paper inventories the environmental releases and wastes associated with the consumption of perchloroethylene in modern dry cleaning machines which ranges from 2.0 to 5.2 kg per 100 kg of clothing cleaned. In addition, water, electricity, and other inputs for both perchloroethylene-based and water-based garment cleaning are compared using data from previous demonstration projects. Toxicological and epidemiological studies provide evidence for the carcinogenicity of perchloroethylene although this classification is controversial. Cancer risks at low levels of exposure associated with modern dry cleaning equipment and good housekeeping practices are unknown and require further investigation. Regardless of these uncertainties, water-based cleaning is preferable to dry cleaning from a human and environmental health perspective. © 1997 Elsevier Science Ltd. All rights reserved

Introduction

A majority of the commercial dry cleaning industry in the United States uses the solvent perchloroethylene to remove soils and odors from clothing. This industry is in a state of transition as older technology is being replaced by more efficient process equipment. Older technology such as transfer machines can result in significant losses of perchloroethylene as clothes are moved from the washer to dryer in an open environment. Newer machines referred to as dry-to-dry machines wash clothes in perchloroethylene and tumble dry them in the same chamber. Regulations designed to protect workers from adverse health effects associated with perchloroethylene are a major driving force for the switch to better technology. Regulations have also encouraged the development of water-based alter-

natives to perchloroethylene-based professional cleaning which are now being investigated in several demonstration projects in the United States[1,2] and Canada[3] .

Perchloroethylene or tetrachloroethylene which is also commonly referred to as perc is a chlorinated organic solvent. Recent environmental assessments of chlorine chemicals are highly controversial. Chlorine chemicals have been targeted for reduction and/or elimination by many governmental and non-governmental environmental organizations due to their persistence, bioaccumulation potential, and toxicity. Policy recommendations have ranged from a total ban on chlorine chemicals to an evaluation of individual chemicals on an individual case basis. The International Joint Commission recommended that

the Parties (US and Canada), in consultation with industry and other affected interests, develop timetables to sunset the use of chlorine and chlorine-containing compounds as industrial feedstocks and that the means of reducing or eliminating other uses be examined[4].

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* To whom correspondence should be addressed.

A subsequent report amended this recommendation by adding the following condition:

recognizing that socio-economic considerations must be taken into account in developing the strategies and timetables[5].

Perc is not as persistent as other chlorinated organic chemicals, and it has a low bioaccumulation potential. Acute health effects from severe exposures to perc are well documented. These include central nervous effects, liver damage, and kidney damage[6,7]. Levels of exposure that lead to these effects, however, are not generally found in well-controlled dry cleaning facilities. A more significant health concern is that perc has been designated as a carcinogen by the State of California, and that the US Environmental Protection Agency's unofficial classification of perc falls in the continuum between possible and probable human carcinogen. The National Institute for Occupational Safety and Health which found significant excesses of esophageal cancer in dry cleaning workers in a 1994 study recommends that perc be handled as a human carcinogen. Perc's status as a potential carcinogen, albeit controversial, along with its widespread use, volatility, and mobility in terrestrial and aquatic environments makes it a considerable health concern facing the dry cleaning industry.

A fundamental policy question can be posed: should the garment cleaning industry invest further resources to improve perc technology, or should the industry support a shift toward aqueous-based cleaning technology or other alternative technologies that may be environmentally preferable? Many dry cleaning establishments using older technology are required by regulations to upgrade by retrofitting or replacing equipment to reduce perc releases to the environment. Alternatively, they have an opportunity to purchase new wet cleaning equipment. Investing in wet cleaning technology represents a much more risky business decision because this technology is relatively new. A complex set of performance, economic, environmental, cultural, and regulatory factors influence the future viability of both water-based and perc-based garment cleaning technologies. The objective of this paper is to provide a framework for analyzing issues influencing design, management, and implementation of more economically and ecologically sustainable cleaning systems.

A multiobjective comparative assessment of perc-based and water-based garment cleaning will be presented. The assessment draws on data from several wet cleaning demonstration projects and previously published studies of the dry cleaning industry[1,3,8,9]. The future direction of professional garment cleaning is guided by key stakeholders including dry cleaners, regulators and policymakers, customers, equipment manufacturers, and other parties. This comparative assessment should serve to enhance the level of understanding of each of their concerns and perspectives. In addition to identifying key issues facing the industry, this paper will highlight information gaps and data uncertainty which may be important to decision makers.

This investigation focuses on commercial cleaners that are often small, independently operated or franchise neighborhood cleaners. Commercial cleaners account for approximately 90% of the dry cleaning industry[8].

Framework for comparative assessment

The methodology for conducting the comparative assessment of the garment cleaning processes is based on the three principles of the life cycle design framework developed for the USEPA which include systems analysis, multiobjective analysis, and multistakeholder participation[10].

Systems analysis

The definition of the system under investigation is a critical element of any comparative assessment. The system is defined by a functional need. In this case, the need is to remove dirt, stains, and odors from clothing and return the clothing to an acceptable clean state. The system components for comparing dry cleaning and water-based cleaning technologies consists of the cleaning process and the garment. The focus of this investigation is on the garment cleaning process rather than on the full life cycle of the garment which also includes the cleaning stage.

Garment component. The garment component can be defined by garment type, the fabric composition, and the degree and type of soiling. Common garment types include bedding, coats, dresses, suits, jackets, pants, skirts, shirts, sweaters, and ties. These garments consist of one or more traditional fabrics such as cotton, polyester, wool, silk, rayon or various blends such as cotton/polyester. The cleaning process can influence the environmental burdens associated with a garment system through its effect on the useful life of the clothing. An environmentally preferable cleaning process which may be more aggressive on the clothing than a conventional cleaning process can shorten the garment's life. This may outweigh the benefits of the environmentally preferable cleaning process.

Cleaning process. This investigation focuses on commercial cleaning of fine washables. Although this study focuses on professional cleaning, fine washables are also cleaned by home hand-washing and home machine-washing on the gentle cycle.

A wide range of dry cleaning processes exist which vary in their capabilities for controlling perc emissions. On a broad level dry cleaning equipment can be classified into transfer machines and dry-to-dry machines. A transfer machine has separate units for cleaning and drying garments. After garments are cleaned in perc in one machine, the operator physically removes them from the wheel or basket of the wash unit and transfers

them to a separate drying unit. Significant releases can occur during the transfer step. In contrast a dry-to-dry machine performs cleaning, extracting, and drying operations in a single unit. Consequently fugitive emissions are significantly less for dry-to-dry machines compared to transfer machines. A 1991 industry analysis found that about 33% of commercial cleaners used transfer machines[11].

Equipment can further be characterized according to the specific type of emissions control technology utilized. In a vented machine the dryer exhaust is released to the atmosphere. A vented machine may be fitted with a carbon adsorber or refrigerated condenser which will remove a majority of the perc in the exhaust stream. In a closed-loop system the dryer air is continuously recycled through the machine. Perc is recovered either through a refrigerated condenser or a carbon adsorber filter.

Emissions factors have been compared for closed-loop transfer and dry-to-dry machines under three emission control scenarios: uncontrolled, refrigerated condenser, and carbon adsorber. Total emissions, which include process emissions and fugitive emissions, were 61% (uncontrolled), 104% (refrigerated condenser), and 93% (carbon adsorber) higher for transfer machines compared to dry-to-dry machines[11]. For this comparative assessment a closed-loop, dry-to-dry unit with a refrigerated condenser was selected because it represents state of the art dry cleaning technology.

Water-based cleaning methods have been classified as either wet machine cleaning or multiprocess wet cleaning. Wet machine cleaning requires both technologically advanced machine washers and dryers. Washers are programmed by an operator to achieve precise control over the desired cleaning time, mechanical action, temperature, and extent of residual moisture in the clothing. The drying operation is also carefully controlled. Garment shrinkage generally occurs at the end of the drying process when the last 10% of the humidity evaporates[3]. Thus, wet cleaners must carefully monitor moisture content to prevent shrinkage. Standard dryers are time and/or temperature controlled while more advanced wet machine dryers monitor humidity level in the exhaust air or the moisture content in garments.

In multiprocess wet cleaning each garment is screened and cleaned by one or more of the following techniques: steaming and spotting, gentle hand washing, heavy scrubbing, and tumble drying.

Although the fundamental dry cleaning process does not vary among practitioners, the configuration of the equipment used to perform the process may vary greatly. In particular, there are several possible combinations of primary and secondary emissions control technology. Even for like configurations, resource use and environmental releases may vary significantly between two practitioners due to differences in operating and maintenance procedures and specific equipment brands. For this reason, estimates in dry cleaning resource use and environmental releases vary

among sources. The same is true for wet cleaning. However, in addition to variations in technology and operating procedures, wet cleaning data are further affected by the relative newness of the process. Due to its short history, there are limited wet cleaning data available.

Multistakeholder analysis

The transition to a more environmentally sustainable garment cleaning system is directly and/or indirectly influenced by various stakeholders listed in *Table 1*.

Garment cleaning trade associations have a key role in educating their memberships about new technologies, regulations, environmental health and safety concerns, and economic considerations. Reductions in perc emissions have been driven by more stringent standards set by government regulators. Health professionals characterize human health and ecological health risks of perc through toxicology and epidemiology studies. These studies provide a basis for regulatory action.

The fashion industry can choose fabrics and construct garments that are compatible with environmentally preferable technologies. Achieving sustainable clothing systems and cleaning systems may, however, require tradeoffs between clothing design for fashion versus design for function. Customers make decisions on the type of fabrics and garments they purchase and how their garments should be cleaned. While performance is a key aspect of customer satisfaction, environmental issues may or may not influence their behavior.

Insurers should consider environmental risks in addition to other basic liabilities. They may set higher premiums for businesses that use perc because of potential site contamination risks or potential medical costs.

Understanding the roles and perspectives of the key stakeholders can lead to partnerships and programs that achieve more significant improvements than what may be possible through insulated approaches.

The University of Michigan study requested data and information from a variety of key stakeholders[8]. In addition, over 21 key stakeholders were provided an opportunity to review their research results. This paper attempts to reflect the views and perspective of the stakeholders most directly influencing garment cleaning systems. The analysis of the roles of garment designers and clothing manufacturers that determine clothing life cycles, however, is outside the scope of this study.

Multiobjective analysis

Performance, economic, environmental burdens, human health, and regulatory factors influencing each garment cleaning system will be evaluated. This paper presents results of the environmental and human health assessments. The analysis of performance, economic, and regulatory factors are presented in a subsequent paper (part 2). Accurate data and information are necessary

Table 1 Garment cleaning stakeholders

Stakeholder	Example
Garment cleaning industry	
Garment cleaners	Individually-owned, franchise or national chain professional cleaners
Equipment manufacturers	Wascomat, IPSO, VIC, Uniclean, Lindus
Cleaning agent manufacturers	Dow, BUFA, Sietz
Trade associations	Neighborhood Cleaners' Association International, Chlorine Council, Chemical Manufacturer's Association
Fashion industry	
Fiber producers	DuPont(CoolMax®, Lycra®). Natural Cotton Colours (FoxFibre®)
Fabric producers	Swift Textiles (denim), Klopman International (polyester/cotton blends), Burlington Industries (textiles for apparel and interior furnishings), Wendell Textiles (interfacings)
Clothing designers	Gucci, Chanel, Ralph Lauren, Gap
Clothing manufacturers	Levi Strauss, Frama PTE Ltd, Grand Prix Associates Inc., Telephon
Trade associations	American Association of Textile Colorists and Chemists, International Fabricare Institute, American Textile Manufacturer's Institute
Other stakeholders	
Customers	
Regulators	US Environmental Protection Agency, Occupational Safety and Health Administration
Educators	National Pollution Prevention Center for Higher Education
Health professionals	National Institute for Occupational Safety and Health, American Conference of Governmental Industrial Hygienists
Investors	Local banks, major financial institutions
Insurers	Insurance providers for individual cleaning facilities

to support policy, design, management, and investment decisions leading towards more sustainable garment cleaning. Performance, economic, and environmental data were compiled from recent demonstration projects and related studies listed in *Table 2*.

An environmental assessment of the dry and wet cleaning processes was based on an input and output analysis of the facility. A comprehensive life cycle inventory analysis of each cleaning system was not conducted. Energy consumption, water use, air emissions, waterborne effluents, and solid waste burdens for each cleaning process were evaluated from demonstration projects and other published sources. Burdens associated with the production of cleaning equipment and perc were not inventoried.

Human health risks associated with perc were characterized from epidemiological and toxicological studies. A review of the major studies and findings will be presented.

Environmental assessment

The environmental assessment inventories the primary resource inputs and environmental releases of both the dry and wet cleaning processes for a standardized unit of clothing equivalent to 100 kg. Garment finishing procedures such as pressing are assumed to be the same regardless of the cleaning method used and, therefore, not considered.

Perc inventory

Estimates of perc usage for dry cleaning for a 100 kg unit of clothing are summarized in *Table 3*. Perc mileage, which is inversely proportional to perc usage, is the amount of clothes cleaned per unit volume of perc. Mileage varies depending upon solvent recovery and emission control technology, level of soiling of clothes, cleanliness standards and housekeeping practices. Three of the four sources in *Table 3* estimate a perc mileage ranging between 62.7 and 80.8 kg of clothes cleaned per liter of perc. The UM study's informal survey of equipment manufacturers, perc manufacturers, and dry cleaning practitioners found estimates of perc mileage for a dry-to-dry machine with a refrigerated condenser to range from as low as 39.9 kg of clothes cleaned per liter of perc (4.07 kg perc/100 kg clothes) to as high as 215.9 kg of clothes cleaned per liter of perc (0.75 kg perc/100 kg clothes)[8].

The USEPA's value for perc mileage, 27.0 kg clothes per liter of perc, is outside the range identified by the informal UM survey. This value as well as the SRRP perc usage value and their resulting perc mileages were derived from a material balance of perc outputs which are based on perc emissions and waste data.

A large portion of the excessive perc usage estimated by the USEPA is attributed to solid waste generation. The USEPA estimated 2.5 kg of perc in the form of solid waste was generated per 100 kg clothes cleaned. Additional information indicates that this solid waste generation factor is high. First, the USEPA solid waste factor was assumed the same for the entire industry of dry cleaners (including industrial, commercial, and coin operated cleaners) regardless of their emission control technology. Second, SRRP reports measured solid waste generation factors for each dry cleaning sector and each emission control technology. The USEPA estimate is inconsistent with their results. SRRP's results range from 0.19 kg of perc per 100 kg clothes to 1.56 kg of perc per 100 kg clothes with the greatest solid waste generation occurring in the coin operated sector.

Table 2 Wet cleaning demonstration projects and related investigations

Project	Principle participants	Data collection/analysis period	Demonstration site	Project overview
Alternative Clothes Cleaning Demonstration Project	Center for Neighborhood Technology (CNT)[1]	September 1994–November 1996	The Greener Cleaner—a 100% wet clean, privately operated facility	A demonstration project which included a series of intensive garment evaluations by outside experts, detailed recordings of costs including start-up and operation expenses and customer satisfaction surveys.
Design for Environment Dry Cleaning Partnership	US Environmental Protection Agency, Office of Pollution Prevention and Toxics (USEPA)[2]	November 1992–December 1992	Neighborhood Cleaners Association New York School of Dry Cleaning—a nonprofit facility which performs both wet cleaning and dry cleaning	A short term, high volume project which compared dry cleaning and multiprocess (non-machine) wet cleaning on economic feasibility and customer satisfaction of garments.
Green Clean Project	Environment Canada (EC)[3]	Phase I June 1994–November 1994	The Green Clean Depot, Finchdal Cleaners and Heritage Cleaners—a 100% wet clean operation consisting of a government run drop-off site and private cleaning facilities using government leased equipment	A project which consisted of wet cleaning demonstrations as well as performance studies of fabric swatches and garments, resource use analysis and customer satisfaction surveys.
		Phase II December 1994–February 1995	The Green Clean Depot and Buttons and Bows Cleaners—a "wet clean with option to dry clean on-site" operation consisting of a privately operated drop-off site and cleaning facility	
		Phase III August 1995–	Langley Parisian —a "wet clean with option to dry clean off-site" privately operated facility	
Comparative Analysis of Perc Dry Cleaning and an Alternative Wet Cleaning Process	University of Michigan, School of Natural Resources Masters students (UM)[8]	April 1994–April 1995	None	A comparative analysis which compiled data from demonstration projects and professional cleaning stakeholders and analyzed dry and wet cleaning with respect to economics, performance, human and environmental health impacts and regulatory requirements.
Source Reduction and Recycling of Halogenated Solvents in the Dry Cleaning Industry	Source Reduction Research Partnership (SRRP) made up of the Metropolitan Water District of Southern California and the Environmental Defense Fund[9]	1986–1992	None	A multi-year field research project which derived perc use and emission values for various dry cleaning technologies through onsite visits, site-specific data gathering and research into dry cleaning processes.

Perc releases

Estimates of perc releases for dry cleaning for a 100 kg unit of clothing are summarized in *Table 3*. EC reported only solid waste releases and categorized these into either number of filter cartridges or liters of hazardous waste still bottoms. EC estimated 0.08 filters were used per 100 kg of clothes cleaned. UM calculated that 0.23 filters were used per 100 kg of clothes cleaned. The difference is attributed to the machine brands and the associated filter technology.

A small amount of waterborne waste is produced as a result of the addition of water to the perc solution during cleaning. Waste water is generally found to contain 150 ppm of perc, which is the water solubility limit[11].

Both SRRP and USEPA agree that the greatest percentage of perc releases is emitted to the air in the form of fugitive and process emissions. Process emissions include losses from muck cookers, stills, and stored residuals such as spent filters. Fugitive emissions result from equipment leaks, solvent transfer, filter changes, and spills.

Wet cleaning has no perc releases. However, wet

Table 3 Perc usage and releases for dry cleaning (dry-to-dry machines with refrigerated condensers) measured per 100 kg of clothes

	EC[3]	SRRP[9]	USEPA[2]	UM[8]
Perc usage				
Perc (kg of perc)	2.01	2.59	5.20	2.48
Perc releases				
Filter cartridges (No. of cartridges)	0.08	n/a	n/a	0.23
Hazardous waste (I still bottoms)	1.08	n/a	n/a	n/a
Solid waste (kg perc)	n/a	0.19	2.50	n/a[c]
Waterborne waste (kg perc)	not measured	very small[a]	1.21E-03[b]	n/a[c]
Air emissions (kg perc)	not measured	2.40	2.70	n/a[c]

[a]SRRP estimated that a carbon absorber dry clean machine would release 1.9 lb of perc per year with an average concentration of 150 ppm. No value for a refrigerated condenser was given.
[b]This estimate is from Radian (1991) and cited in the USEPA document [2].
[c]For solid waste, waterborne waste and air emissions, UM cited SRRP and USEPA figures.

cleaning has other releases, primarily waterborne wastes such as phosphorus, metals, and suspended solids. Both EC and CNT tested the wastewater discharge from their demonstration sites and found that discharges of wet cleaning effluent were within acceptable limits and would likely meet sewer treatment requirements without additional treatment[1,3]. Exceptions may exist if a wet cleaner continually cleaned excessively soiled clothes such as contaminated shop clothes. However, these are typically cleaned by industrial processors and not commercial dry cleaners.

Water use

Table 4 summarizes the total water use for both dry and wet cleaning. The discrepancy in UM and EC estimates for water consumption in the dry cleaning process is due to the different emission control technologies. The EC demonstration site used chiller water in conjunction with its refrigerated condenser. This non-contact water was used only once and then discharged to the sewer system. EC states that although recycling chiller water is possible, it is not economical for small facilities which make up 85% of Canadian plants[3]. UM used a similar emission control configuration in their model analysis. However, the UM configuration was assumed to recycle all the chiller water.

According to all sources, wet cleaning uses more water per 100 kg of clothing than dry cleaning. CNT measured water use per 100 kg of clothes cleaned to

be in the range of 3338–5008 liters. The CNT estimates are based on a year of data collected at a demonstration site which cleaned over 31 000 garments in that time. EC's data are based on a single month of operations, and EC measured a much lower value of 1258 liters. EC's value includes only the actual water used by its wet clean machine. UM reported all water used during the cleaning process, therefore, including water used during manual cleaning (120 liters per 100 kg of clothes cleaned) as well as during machine cleaning (2171 liters per 100 kg of clothes cleaned). The CNT estimate likewise reflects cumulative water use for the entire wet cleaning process. In addition CNT estimates that water use for a wet cleaner could be reduced by as much as 25–34% over time as the operator develops expertise with the process.

Electricity use

Table 4 summarizes the total electricity use for both dry and wet cleaning. EC found that dry cleaning required 28 kWh of electricity per 100 kg of clothes cleaned. UM estimated a total electricity requirement of 39 kWh per 100 kg of clothes cleaned. Of the 39 kWh total, the UM study estimated that 14 kWh were required to operate emission control technology while the remaining 25 kWh was required for the cleaning unit.

Similarly, for wet cleaning, EC again measured an electricity requirement which was less than that esti-

Table 4 Utilities for wet and dry cleaning measured per 100 kg of clothes

Utility	Wet				Dry	
	EC[3]	UM[8]	CNT[1]		EC[3]	UM[8]
			Low	High		
Water (l)	1258[a]	2291	3338	5008	1026[b]	1
Electricity (kWh)	8	17	—	—	28	39
Natural gas (kWh)	238	—	—	—	167	—

[a]Estimate does not include any water used in steam or manual cleaning.
[b]Unlike UM, EC utilized a refrigerated chiller which did not recycle water.

mated by UM. The washing operation most likely can account for this difference. The IPSO machine used by EC has an average cycle time (15 min) half that of the AquaClean machine (30 min) used in the UM study. Furthermore, the AquaClean is capable of stronger extractive forces which require more electricity.

Both sources agree that dry cleaning requires more electricity than wet cleaning. The greatest contributor to this is the air recirculation and refrigeration required for solvent recovery.

Natural gas

Table 4 summarizes the total natural gas use for both dry and wet cleaning. Natural gas is used in dry cleaning to power the boiler to generate steam for heating, cleaning, and pressing. It is difficult to allocate steam use for these individual activities. The UM study estimated that approximately 20% of steam generated by a typical boiler utilizing natural gas is used to provide steam to the dry cleaning machine[8]. A small amount is also used at infrequent intervals to operate the still cookers.

Natural gas is used in a similar fashion in wet cleaning as in dry cleaning. EC estimated that the wet cleaning machine would require more natural gas generated steam than a dry cleaning machine per 100 kg of clothes cleaned. EC noted that the estimated steam consumption for the dry cleaning machine was actually higher per load than for the wet clean washer and dryer[3]. However, the dry cleaning machine was capable of cleaning larger and, therefore, fewer loads, reducing its overall natural gas consumption.

Chemical use

Table 5 summarizes the total cleaning agent use for both dry and wet cleaning. Both the UM and the EC studies estimated that the same quantities of spotting solvents were used in both dry and wet cleaning. Furthermore, both studies agree that wet cleaning requires the use of more sizing and finishing agents. Data on detergent use are inconsistent while data on detergent composition are unavailable. A preliminary assessment by EC indicated that these chemicals are not hazardous and are classified as household detergent products[3].

Human health assessment

It is well demonstrated that exposure to perc at high levels poses serious human health risks including damage to the central nervous system, early onset of liver and kidney damage, and temporary impairment of vision[3,6,8]. Exposure to high levels of perc, however, is not common in modern dry cleaning facilities that use dry-to-dry technology. A much more difficult and controversial health issue is the carcinogenic potential of perc and the health risks from long-term low level exposures.

Non-Cancer health effects of perc

Studies have linked perc with a host of health effects. Clinical studies, following short-term exposure of volunteers to a variety of concentrations of perc, ranging from 106 to 2000 ppm (719 to 13 560 mg/m^3), documented symptoms ranging from mild eye and nasal irritation to dizziness and unconsciousness[12,13]. High levels of exposure can lead to "toxicity to the central nervous system which can result in coma, respiratory paralysis, or circulatory failure" or even death[6,14,16]. With increased concentrations of perc, the severity of the effects increased while the time of onset became shorter. However, even at current Occupational Safety and Health Administration (OSHA) permissible exposure levels (PELs) of 100 ppm, light-headedness, speech difficulties, nausea, and eye and throat irritation were observed in male and female volunteers exposed for 7 hours/day for 5 consecutive days[17].

Long-term exposure at levels below 40 ppm, well within the PELs, has been linked to subclinical neurobehavioral effects[18] such as psychological effects on personality, mood, and attention; and visual/spatial function, sensorimotor, intellectual, memory, and coordination functions[19,20]. Long-term occupational exposure has also been found to cause "clinical and preclinical effects upon frontal lobe and limbic functions [the frontal lobe 'affects a person's reliability, emotional stability, ability to reason, and ability to maintain self control,'[21] and limbic functions relate to vision]."

Research into potential effects on reproductive functioning has been conducted, but further research is needed. A study done by Rachootin and Olsen reported an "increased risk" of idiopathic ["of unknown causation"[21]] infertility in females and exposure to dry

Table 5 Cleaning agents for wet and dry cleaning measured in liters per 100 kg of clothes

	Wet		Dry	
	EC[5]	UM[8]	EC[3]	UM[8]
Detergent	0.46	1.40	1.08	0.83
Sizing/finishing agent	0.70	2.81	0.39	0.00
Spotting solvents	0.15	0.37	0.15	0.37

cleaning chemicals[22]. "A Finnish study of pregnant dry cleaning workers found miscarriage rates three times higher than normal"[23]. However, some studies have been unable to verify this increase in spontaneous abortion and congenital malformations among dry cleaning workers[24]. Further, the studies suffered from a lack of data concerning the type(s) of dry cleaning chemicals involved and the intensity of exposure to perc or other chemicals.

A study of the effects of perc exposure on human semen quality found that sperm in dry cleaners were "significantly more likely to be round...and less likely to be narrow...than the sperm of laundry workers." In addition, "sperm of dry cleaners tended to swim with greater amplitude of lateral head displacement (ALH) [and less linearity] than those of laundry workers"[25]. Round sperm are found in men who are infertile as these sperm are unable to penetrate the ova. Many of the studies done on reproductive functioning "support the hypothesis that perchloroethylene affects the hormone system"[26]. However, due to small sample sizes and other limitations, the findings are often not conclusive.

Carcinogenic potential of perc

Determining the level of cancer risk from exposure to perc is a complex and highly debated issue. A number of studies have examined the effects of perc on animal and human populations, yet their findings have been subjected to varied interpretations within the scientific community. Brown and Kaplan observed in a 1987 National Institute for Occupational Safety and Health (NIOSH) study an excess risk for urinary tract cancer in a retrospective study of workers employed in the dry cleaning industry[27]. A subcohort of workers employed in shops that used only perc as their primary solvent, however, did not indicate an excess risk of cancer. The 1994 study of Ruder *et al.* sponsored by NIOSH and National Institute of Environmental Safety and Health updated, confirmed, and strengthened the findings of the Brown and Kaplan study[28]. Their findings indicated significant excess bladder cancer mortality and elevated digestive tract cancer mortality in dry cleaning workers who had worked for at least 1 year before 1960 at a shop using perc as the primary solvent and who were not known to have been exposed to carbon tetrachloride. In addition, the 1994 study found a significant excess of esophageal cancer deaths among perc-only workers with 5 or more years of employment and 20 or more years of latency[28].

The USEPA Science Advisory Board (SAB) has classified perc on a continuum between a B2 (probable human carcinogen) and C (possible human carcinogen)[29]. Although, according to the SAB, a lack of interpretable epidemiological data prevents perc from being classified as a B2 compound, the evidence supporting a B2 classification is stronger than for most other compounds classified as possible human carcinogens (C). For a "C" classification, the evidence must merely "confirm that [the compound] should be

considered as an animal carcinogen." In the case of perc, the SAB cites evidence showing "liver tumors in male and female mice, kidney tumors in male rats, and, possibly, mononuclear cell leukemia in male and female rats" as sufficient for meeting a "C" classification.

The USEPA has adopted the SAB recommendation for the classification of perc, that is, that perc is classified on a continuum between a B2 (probable carcinogen) and C (possible carcinogen)[30]. The USEPA also decided to categorize perc as a Category I contaminant for drinking water regulation. Category I chemicals are those where the USEPA feels there is "strong evidence of carcinogenicity." Since perc is a volatile organic compound and was classified as a Category I contaminant, as a matter of policy, the maximum contaminant level goal (MCLG) was set at zero.

In 1989, in an attempt to reevaluate the PEL for perc, OSHA set new standards lowering the PEL for perc from 100 ppm to 25 ppm. OSHA concluded that "perchloroethylene is a potential human carcinogen that presents a significant risk of material health impairment to workers exposed to it in their places of work"[31]. As a result of an industry challenge, in July 1992 an appeals court overturned the PELs, and they reverted back to their former level, in the case of perc, 100 ppm.

Although the SAB feels the weight of evidence of carcinogenicity in humans is not sufficient to classify perc as a probable human carcinogen, other groups disagree. Since 1977 with the release of the National Cancer Institute's bioassay results showing an excess of hepatocellular carcinomas in male and female mice, NIOSH has recommended that "perchloroethylene be handled as if it is a human carcinogen, minimizing exposure to the lowest level possible"[6]. In California, perc is classified as a known carcinogen[9]. In 1987, the International Agency for Research on Cancer (IARC) classified perc as a category 2B carcinogen (i.e. a substance for which the evidence in animals is sufficient)[31]. The New York Department of Public Health set a maximum indoor air concentration of perc at 15 ppb in homes[23].

A 1993 study conducted by the Massachusetts Department of Public Health and sponsored by Boston University examined populations served by water contaminated when perc leached into the drinking water from the "inner vinyl lining of certain asbestos cement water distribution pipes"[32]. The researchers reported an increased risk of leukemia and bladder cancer. For both leukemia and bladder cancer, the study found that the increased risk was related to the dose imbibed. These findings suggest that the carcinogenic potential of perc "is a matter of significant public health concern"[32].

Numerous other studies have reported elevated risks of urinary tract, esophageal, and pancreatic cancers in dry cleaning workers, but most of these studies did not investigate a specific dry cleaning solvent[28].

Exposure pathways

Recent studies have identified a number of exposure pathways affecting both dry cleaning workers and others not employed by the industry[7,33-35]. Employees of dry cleaners are exposed to perc vapors in the shop air and through dermal contact. The public can be exposed through contaminated drinking water supplies, absorption of perc by food products, absorption by building materials and movement of vapors into apartments above and adjacent to dry cleaners, off-gassing from dry cleaned clothes, and bioconcentration in plants and animals.

Dry cleaning workers: inhalation and skin contact. The main route for human exposure to perc is by inhalation, although absorption through the mouth and by skin contact is also important[36]. Within a dry cleaning shop using closed-loop, dry-to-dry machines with refrigerated condensers, fugitive emissions can be released from a number of sources: opening of the machine door (especially when the fan to control emissions is malfunctioning), storage of perc and spent filters, leaking equipment, poorly maintained equipment, vaporization of wastewater, improperly dried clothes, regular maintenance and cleaning of stills, spotting boards, and filter replacement[33]. Perc emissions can also occur while new perc is transferred into the cleaning machine. With the newest technology, however, perc can be transferred from specially designed containers which hook onto the dry cleaning machine, and the solvent is then transferred by means of a pump. Dry cleaners are required to provide adequate ventilation. However, shops with poor housekeeping practices may postpone repairing broken fans. This lack of proper ventilation can significantly increase the degree of perc exposure[34]. Other potential sources of contamination result from spills, leakage, and boil-over of a cooker or still[16]. Several studies monitoring perc emissions in the workplace have found elevated concentrations particularly from malfunctioning equipment[33,34].

Solet et al. investigated dry cleaning worker exposure to perc by collecting exhaled breath samples and breathing zone air samples from transfer, dry-to-dry, and mixed mode facilities[37]. Solet et al. found that the mean for breath samples taken in transfer facilities was over five times that measured in dry-to-dry facilities, and mean transfer facility air samples exceeded samples from dry-to-dry facilities by over four times. No air samples collected in dry-to-dry facilities exceeded the OSHA PEL of 25 ppm [the existing standard during their study]. The mean breath sample concentration was 1.47 ± 1.24 ppm and the mean air sample was 7.09 ± 6.40 ppm for the dry-to-dry facilities investigated. Operators were exposed to significantly higher perc concentrations compared with non-operators including pressers, clerks, and managers.

Materna also studied occupational exposure to perc in the dry cleaning industry[34]. Personal sampling measurements yielded time weight average exposure levels of 28.3 [range 3.0–75.9] ppm for dry-to-dry operations and 86.6 [range 28.5–302.7] ppm for transfer operations.

Off-Gassing. In addition to direct emissions from dry cleaners, individuals inadvertently increase their exposure through the perc retained in dry cleaned clothes that they bring home. The process by which the perc evaporates from the clothes is know as off-gassing. Particularly problematic materials are acetate and nylon, "which are highly hydrophobic" and can hold higher amounts of residual TCE, a perc by-product, than other fibers[38]. Studies have measured significantly high levels of perc due to off-gassing from clothing that was dry cleaned[39,40]. Studies measuring off-gassing from clothes that were cleaned specifically by the dry-to-dry process, however, were not available. New technology is much more effective in reducing the level of residual perc in clothing.

Ingestion: food and water. Individuals are also exposed to perc through the foods and liquids they ingest. Perc accumulates readily in fatty foods. A British Broadcasting Corporation study found perc concentrations of almost twice the "safe" limit in butter in grocery stores near dry cleaners. Perc was also found in other fats and dairy products in restaurants near dry cleaners[35,41]. Perc is transmitted to breast milk, and it is not known whether this may cause damage to infants of exposed nursing mothers[42].

Drinking water has also proven to be a source of human exposure. Perc has entered the water supply through two primary means: groundwater contamination from dry cleaning establishments[7] and vinyl liners used on the inside of water pipes[32]. In some EPA surveys, 14–26% of groundwater and 38% of surface water sources have some degree of perc contamination, a matter of "significant public health concern"[32].

Health effects of wet cleaning

The wet cleaning process has been used in professional cleaning facilities for a relatively short period of time. Thus far, no studies have evaluated the health effects of this system.

In preliminary health analyses of wet cleaning, the primary concern raised is the exposure of wet cleaning operators to solvents during the spotting process. However, since some wet cleaners have found nontoxic solutions to substitute for the spotting solvents, and other wet cleaners continue to use the solvents used in dry cleaning, human exposure due to spotting solvents can be considered equivalent for both the wet and dry cleaning systems for this comparative analysis and will not be studied separately.

Conclusions

The data presented here clearly indicate that wet cleaning has lower overall environmental burdens and

human health risks compared to dry cleaning. The dry cleaning impacts of most concern to the environment and human health accrue from the use of perc, which results in emissions to the air, land, and water.

Perc mileage in the range of 62.7–80.8 kg of clothing cleaned per liter of perc is a measure of the total perc consumption for a commercial garment cleaner. Perc usage results in environmental impacts related to air emissions, water contamination and solid waste. Although the industry switch to dry-to-dry technology has dramatically reduced process emissions, worker exposure to fugitive emissions remains a health concern especially for poorly maintained facilities. In addition, ongoing releases of perc in separator water and through accidental spills is a source of site and water contamination. Furthermore, dry cleaning requires more electricity than wet cleaning because of the need for emission control technology but uses a negligible amount of water if emission controls are fitted with chiller water recirculation equipment.

In contrast, wet cleaning produces no direct air emissions at the facility level and no hazardous waste. However, wet cleaning requires more water to clean garments which may pose a significant concern in areas where water resources are limited. Future developments in water recycling, reuse, and on-site treatment may substantially reduce the amount of water required.

The acute human health effects of perc including central nervous effects, liver damage, and kidney damage are well documented. Although its carcinogenicity is still controversial, much evidence from epidemiological and toxicological studies supports a cancer-causing linkage. Several of the key epidemiological studies, however, analyzed the dry cleaning industry as a whole and, therefore, did not distinguish effects specific to dry-to-dry equipment with refrigerated condensers. As equipment and housekeeping practices improve, levels of exposure to perc will continue to decrease. Current regulations are expected to reduce perc emissions particularly those regulations driving the elimination of transfer machines. Recognizing this trend, health risks such as cancer, reproductive health effects, subclinical neurobehavioral effects, and health risks at low levels of exposure need to be assessed further.

While the dry cleaning industry has the potential to improve perc mileage and reduce perc releases, perc is inherently toxic and can pose significant human health concerns even though the incidence of realized health effects may be very low. Whether these lower level risks are significant enough to drive further research and development into water-based cleaning depends in part on regulatory pressures, economic forces, and the performance criteria that influence both cleaning technologies. These three factors are analyzed in part 2 of this paper series.

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