An Investigation into the Potential for PVC Reduction in Building: Drainage Lines

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ABSTRACT:

This report analyzes the detrimental effects of toxic chemicals released from leaching, production and degradation of PVC drainage lines in residential and institutional projects. The main toxic chemicals that are of concern are phthalates and dioxins. These have been shown to cause many diseases to humans and significantly impact the environment. The report discusses three alternatives: ABS, Bio – Vinyl, and HDPE. Preliminary analysis determined HDPE as the most effective replacement for PVC; thus, a triple bottom line assessment focussed on comparing PVC with HDPE.

As HDPE is relatively new to drainage applications, the research on its impacts were limited. Furthermore, some of the primary sources that were utilized were uncertain of the processes used in producing both types of plastics. Other primary sources were contacted for specific details, but some sources did not reply. In this report, it was assumed that residential and institutional drainage line processes were the same and so they were treated under the same category. Additionally, as many manufacturers fluctuated in prices, in general, specific prices were not used as a comparison. The economical comparison was based on prices relative to one another. Interior uses of these plastics were also assessed and this was assumed to involve the use of the plastic for small-scale projects such as sink drains.

Through researching HDPE, it was found that the significant advantage it held over PVC was its flexibility and durability. This enabled HDPE to utilize fewer joints and require less equipment for installation. Also, HDPE had minimal negative impacts towards human health as only one compound, degraded HDPE, was found to be released, which did not pose as serious a threat to those released from PVC. Although HDPE released fewer carbon emissions in the production stage, over an entire lifecycle it produced more carbon emissions; however, the journal articles used made assumptions that could be vary.

Furthermore, HDPE pipes were found to be less expensive compared to PVC, but the overall price of HDPE pipes including the fittings cost slightly more than PVC due to the complexity of the fittings required. However, it was found that some of these costs could be recovered during installation since the flexibility of HDPE enabled less fittings to be used. These determinants indicated that HDPE is a suitable replacement for PVC drainage lines as the benefits related to HDPE outweigh the benefits associated with PVC.

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LIST OF ILLUSTRATIONS:

GLOSSARY:

Asthma: a respiratory condition marked by attacks of spasm in the bronchi of the lungs, causing difficulty in breathing

Bio-plasticizer: a substance (typically a solvent) derived from acidic compounds found in plants and added to a synthetic resin to produce or promote plasticity and flexibility and to reduce brittleness

Butt Fusion: the joining of two pieces of plastic or metal pipes or sheets by heating the ends until they are molten and then pressing them together to form a homogeneous bond

Carcinogen: a substance capable of causing cancer in living tissue

Cholestasis: a condition in which little or no bile is secreted or the flow of bile into the digestive tract is obstructed

Continuous Service Temperature: the highest temperature at which a material can perform reliably in long term application

Dioxin: a highly toxic compound produced as a by-product in some manufacturing processes, notably herbicide production and paper bleaching. It is a serious and persistent environmental pollutant

Eczema: a medical condition in which patches of skin become rough and inflamed with blisters which cause itching and bleeding

Embodied Energy: sum of all the energy required to produce any goods or services

Endocrine System: the system of glands that produce endocrine secretions that help to control bodily metabolic activity

Feedstock Recycling: Recycling process which decomposes materials into reusable components

Gravity Flow: the flow of a fluid drawn through a conduit under the force of gravity

Greenhouse Effect: the trapping of the sun's warmth in a planet's lower

	atmosphere, due to the greater transparency of the atmosphere to visible radiation from the sun than to infrared radiation emitted from the planet's surface
Leach:	to remove soluble or other constituents from by the action of a percolating liquid
Lipid Soluble:	ability of a chemical compound to dissolve in fats, oils, lipids, and non-polar solvents
Low Head Pressure:	water left in the pipe after a valve is turned off that is gently flowing out of a low elevation head
Melting Index:	a measure of the ease of flow of the melt (liquid-form) of a thermoplastic polymer
Plasticity:	the quality of being easily shaped or moulded
Phthalate:	any of various salts or esters of phthalic acid used especially as plasticizers and in solvents
Polyethylene:	a tough, light flexible synthetic resin made by polymerizing ethylene, chiefly used for plastic bags, food containers, and other packaging
Polypropylene:	a synthetic resin which is a polymer of propylene, used chiefly for films, fibres, or moulding materials
PSM:	not an acronym, arbitrary designation for a product having certain dimensions
Resin:	a solid or liquid synthetic organic polymer used as the basis of plastics, adhesives, varnishes, or other products
Rhinitis:	inflammation of the mucous membrane of the nose, caused by a virus infection (e.g. the common cold) or by an allergic reaction (e.g. hay fever)
Slip Agent:	additive used to provide lubrication during and immediately following processing of plastics
Solvent:	the liquid in which a solute is dissolved to form a solution
Solvent Weld Joint:	a pipe joint made by spreading a cement on two plastic surfaces to be joined. The cement reacts chemically with

these surfaces, thereby dissolving the material. Then these two surfaces are placed in contact; a solid joint is formed when hardening takes place

Stress Crack: an external or internal crack in a solid body (metal or plastic) caused by tensile, compressive, or shear forces

Thermal Expansion: thermal expansion is the tendency of matter to change in volume in response to a change in temperature

Thermal Stabilizer: a material that helps polymers endure the effects of increased heat

Thermoplastic: denoting substances (especially synthetic resins) that become plastic on heating and harden on cooling, and are able to repeat these processes

LIST OF ABRIEVIATIONS:

ABS:	Acrylonitrile Butadiene Styrene
BC:	British Columbia
CO_2:	Carbon Dioxide
CSA:	Canadian Standards Association
CPVC:	Chlorinated Polyvinyl Chloride
BBP:	Benzyl Butyl Phthalate
DBP:	Dibutyl Phthalate
DEHP:	Di-2-ethylhexyl Phthalate
DEP:	Diethyl Phthalate
DMT:	Dimethyltryptamine
EPA:	Environmental Protection Agency
GHG:	Greenhouse Gas
HDPE:	High Density Polyethylene
PE:	Polyethylene
PSM:	See Glossary
PVC:	Polyvinyl Chloride
UV:	Ultraviolet

1.0 INTRODUCTION

Polyvinyl chloride, better known as PVC, is a widely used plastic in the construction industry. Its long history has improved production and enabled PVC to be manufactured at a low cost. Despite PVC's popularity, recent research has shown adverse consequences that arise from its uses (Arseen, 1997; Environmental Protection Agency, 2007). Studies indicate that PVC releases two groups of chemical compounds throughout its lifecycle: dioxins and phthalates (Arseen, 1997). Dioxins and phthalates both impose a serious threat to human health and the environment. Additionally, due to the large demand of PVC, the disposal of associated wastes is also a significant contributor to pollution (Brown et al., 2000). There have also been reported problems regarding the construction aspects of PVC. PVC has some unfavorable properties that may impede construction projects. Thus, an alternative is required and needs to be assessed to determine whether it is a viable option and could effectively replace PVC.

This investigation will focus on the drainage aspect of plastic piping for industrial and residential projects. For our analysis, however, it was assumed that the processes involved in these two divisions were the same. A preliminary study will first be outlined that describes an evaluation of the following plastics: ABS, Bio-Vinyl and HDPE. From this, the top candidate that will be researched as a replacement for PVC piping will be determined. The selected alternative will be compared to PVC by utilizing the triple bottom line assessment.

The triple bottom line is divided into three categories: social, environmental, and economical, in order to fully understand the alternative. The analysis will be heavily weighted by the economic aspects of the two plastics as this holds the most influence in any project, but health risks, GHG emissions and construction methods will also be part of the comparison. By conducting this assessment, the advantages and drawbacks of the alternative will be understood and it will be determined whether this option is suitable as a replacement for PVC drainage systems.

2.0 DISCUSSION OF THE ALTERNATIVES

Through preliminary research three alternatives to PVC drainage systems were discovered. These included: ABS, Bio-Vinyl and HDPE. To determine the best-suited alternative of the three, primary research was conducted and journal articles were assessed.

ABS piping is typically used for small-scale household drainage systems (i.e. piping for sinks); but, some companies do manufacture and implement large-scale piping. Due to the lower demand for large-scale ABS piping, the price is generally much greater than the price of PVC piping (see Appendix A). Furthermore, certain properties of ABS are not desirable for large-scale drainage applications such as a poor solvent resistance and a low continuous service temperature (Xcentric Mold & Engineering, n.d.).

Bio-Vinyl is a relatively new piping material; thus, little knowledge of the benefits of Bio-Vinyl could be found. Dr. Ko (in Appendix B) suspected that Bio-Vinyl uses bio-plasticizers instead of phthalates. Bio-plasticizers are a chemical compound derived from a specific acid harvested from plants such as corn (see Appendix B, [24]); thus, the leaching of phthalates would no longer occur. Despite lower carbon emissions, the synthesis of Bio-Vinyl still requires production of some PVC components (Vierira, da Silva, dos Santos, & Beppu, 2011). It was unknown whether this process could have produced dioxins similar to those generated from PVC. The manufacturer of Bio-Vinyl was contacted but they did not respond to our questions. Therefore, only a limited amount of information was collected.

HDPE is a widely used pipe for drainage applications and exhibits many favorable properties such as high flexibility, good durability and ease of installation (Hydrogold Int'l Water Management Consultants, 2012). HDPE is commonly used for medical containers and devices such as syringes (see Appendix B). Since HDPE is used in hospital environments, the standards regarding the chemical properties of HDPE must be strict to ensure the well-being of the patient. Appendix A shows that HDPE is known to not leach any harmful chemicals. Furthermore, HDPE releases less carbon dioxide (CO_2)

emissions during the production phase, it releases more in the overall lifecycle than PVC [21]. In addition, the overall cost of HDPE pipes is slightly more than that of PVC pipes (Piratla, Ariaratnam, & Cohen, 2012).

From this preliminary research, HDPE was selected as the primary focus for this investigation because it showed the most promise to effectively replace PVC for drainage applications.

3.0 SOCIAL IMPACT

The analysis of the social concerns for HDPE and PVC piping will assess the number of potentially toxic compounds released through each plastic's lifecycle and the risks they could impose on the general populace. Additionally, interior uses and the differences between installation practices will be investigated. From this, the social effects that each plastic could impose for drainage applications will be understood.

3.1 TOXIC COMPOUNDS

Over the past several years authors have acknowledged the toxic effects of PVC on human health (Bertazzi et al., 2001). The two groups of chemicals arising from PVC that are associated with these toxic effects are dioxins and phthalates. Dioxins are a harmful group of compounds that are generated during the production process of PVC and are released into the atmosphere (Arseen, 1997). Phthalates are specific chemicals used to increase the plasticity of PVC and are known to leach from the plastic and into the environment (Heudord, Mersch-Sundermann, & Angerer, 2007). Some of these dioxins and phthalates have been discovered to cause reproduction problems by interfering with the human endocrine system (Bertazii et al., 2001; Heudord et al., 2007). European countries such as Sweden, Denmark, and Spain are aware of these dangers and have banned the use of PVC (Healthy Stuff, 2013). They have adopted the use of Silicone or polyethylene (such as HDPE) as an alternative for their products as opposed to PVC (Health Care Without Harm, 2006). The piping and drainage industry in Canada, on the other hand, still uses PVC despite the considerable health risks (Bertazzi et al., 2001; Heudord et al. 2007).

Plastic	Processing	Leaching and Degradation	Total
PVC	17	5	22
HDPE	1	1	2

Table 1: The number of potentially toxic compounds emitted during production, leaching, and degradation of PVC and HDPE.
Retrieved from (Arseen, 1997)

According to Table 1, the number of toxic compounds emitted from PVC production and leaching is far greater than the amount of toxic compounds emitted from HDPE. The 17 toxic compounds from PVC processing are identified to be various types of dioxin molecules (Arseen, 1997). Although other dioxin molecules are also released during PVC processing, only 17 of these have been classified as potentially toxic (Arseen, 1997). The 5 toxic molecules that arise from PVC leaching and degradation were identified to be different types of phthalates (e.g. BBP, DBP, DEHP, DEP, and DMT) (Environmental Protection Agency, 2007).

Unlike PVC, HDPE has far fewer toxic compounds released during production and leaching. According to Appendix A, no harmful by-products are generated during HDPE production and the leaching that occurs in PVC piping is non-existent in HDPE pipes. Contrary to this statement, further research found that HDPE does actually produce a potentially dangerous chemical known as degraded HDPE (see in Table 1) (Al-Khatim & Ali, 2006; New Zealand Institute of Chemistry, 2005). This contradiction illustrates that Appendix A might be biased due to encouraging plastic use. When comparing the total number of toxic compounds released from PVC and HDPE, it was found that PVC released more toxic chemicals, therefore, it is rated as having a higher toxicity risk.

3.2 HEALTH RISKS

The toxic compounds generated from PVC piping are known to have a variety of health effects on humans and animals. The toxic dioxins released from PVC production are known to act as carcinogens as well as endocrine, reproductive, and cardiovascular system disruptors in humans [4]. Workers involved in PVC production face a greater risk of dioxin exposure and its adverse health effects. Investigations into the effects of the various types of phthalates used in PVC have been conducted on rats and medical cases have also been reported. The findings have been summarized below:

- BBPs are known to cause eczema and rhinitis in children
- DBP was linked to defects in male reproductive organs in rats
- DEHP was associated with increased incidences of asthma, cholestasis, and unusual lung disorders in children
- DEP exposure has resulted in abnormal sperm and decreased testosterone levels in rats
- DMT exposure resulted in chronic kidney inflation in rats

(Environmental Protection Agency, 2007)

Exposure to phthalates contained in PVC seems to affect children to a greater extent than adults. Furthermore, the adverse effects of phthalates reported in mice are also expected to have similar effects on humans.

HDPE, when compared to PVC, has minimal health risks; however, it still releases compounds that may prove to be toxic to humans (Al-Khatim & Ali, 2006). The compounds labeled as toxic in Table 1 from processing and leaching were both identified as degraded HDPE; and when ingested, it was shown to have negative impacts on the reproductive systems of rats (Al-Khatim & Ali, 2006; New Zealand Institute of Chemistry, 2005). Studies have not been conducted on humans; however, it is possible that similar results on human reproductive systems are expected if exposed to high enough quantities of degraded HDPE (Al-Khatim & Ali, 2006). Table 2 summarizes the known diseases that are associated with the toxic compounds that could be released from either PVC or HDPE. Note that 'potential' refers to diseases that have only been detected in animal test subjects.

PVC	HDPE
Carcinogen	Potential Reproductive disorders
Endocrine Disruptor	-
Reproductive Disruptor	-
Cardiovascular effects	-
Asthma	-
Eczema	-
Rhinitis	-
Cholestasis	-
Lung disorders	-
Potential kidney inflation	-
Potential Sperm disorder	-

Table 2: Potential and known diseases and adverse health effects caused by PVC and HDPE. Retrieved from (Al-Khatim & Ali, 2006; Environmental Protection Agency, 2007)

3.3 INTERIOR USE CONCERNS

The major concern with interior use of PVC piping is that the phthalates can leach off either into the contents of the pipe or into the surrounding environment (Environmental Protection Agency, 2007). For example, if a pipe carrying drinking water is composed of PVC, phthalates from the PVC will leach into the drinking water. This effect has been acknowledged by the EPA, as phthalates have been found in drinking water (Environmental Protection Agency, 2007). HDPE does not contain phthalates though; thus, the toxicity risk to humans is lower. HDPE might eventually degrade and enter drinking water, but the amount that is released would be at very low concentrations and therefore would be unlikely to cause any serious problems to human health.

3.4 VARIANCE IN CONSTRUCTION

During the construction and installation process, HDPE also has several benefits over PVC. Since HDPE can be delivered in longer lengths and is more flexible, a smaller number of joints are required to join the pipes together (MRI Water Solutions, 2011). Therefore, the installation time could be decreased. However, an issue with HDPE is that it is easily subjected to thermal expansion (MRI Water Solutions, 2011). If an excess of heat is applied to the HDPE pipe, it may deform the pipe and prevent any further installation. Despite these possible faults that could arise, HDPE is recognized by the BC building code as being code compliant (British Columbia Piping Code, 2012) (see Appendix C).

3.5 SOCIAL IMPACT SUMMARY

It was found that HDPE presented a greater net positive social impact than PVC due to its smaller amount of toxic compounds, minimal health risks and greater ease in construction procedures.

4.0 ENVIRONMENTAL IMPACT

An essential method for measuring sustainability is to evaluate the environmental effects associated with producing the material. In order to analyze the environmental impacts of HDPE and PVC, the number of chemicals released will be re-addressed followed by a comparison of CO_2 emissions, consumption of energy, and disposal of waste.

4.1 CHEMICALS GENERATED VIA PRODUCTION, LEACHING AND DEGRADATION

As discussed in the social impact section, PVC generates a larger amount of chemicals throughout its lifecycle than HDPE which was illustrated in Table 1. The environmental aspects of these compounds are also detrimental. The dioxins released during PVC production are lipid soluble compounds; and therefore, can easily penetrate through not only the skin of humans, but animals as well (Rumak, Khanh, Kuzentsov, Sofronov, & Pavlov, 2009). Once inside a host, dioxins can cause the onset of several diseases such as cancers and reproductive failures (Bertazzi et al., 2001). As dioxin passes through the food chain from predator to prey, the content within the predator increases in concentration (Rumak et al., 2009); thus, the host is more likely to experience the toxic effects related to dioxins [23]. Dioxin is also known to cause defoliation of forests, destruction of coral communities in the sea, and chemical pollution of soils which prevent any future growth or harvesting of plants (Rumak et al., 2009). Overall, dioxins have a tremendous amount of negative impacts on animals as well as the ecosystem.

According to Table 1, HDPE was shown to release only one potentially dangerous compound which was degraded HDPE. If this compound happened to enter nearby water supplies, the concentration of degraded HDPE would be expected to be low; therefore, it would have minimal consequences (Al-Khatim & Ali, 2006; New Zealand Institute of Chemistry, 2005). Since PVC produces a much larger array of chemicals than HDPE, it can be concluded that HDPE has a lower environmental impact related to these compounds. However, CO_2 emissions must also be assessed to either verify or disprove this assumption.

4.2 CO_2 EMISSIONS

CO_2 is one of the major contributors to the amplification of the greenhouse effect. Although it is inevitable that CO_2 will be released throughout the lifecycle of any type of drainage pipe, it is important to consider all of the factors that could reduce emissions. Dr. Kalyan Piratla (2012) and his team investigated the CO_2 emissions of four types of plastics used as water pipelines, two of which were PVC and HDPE. Figure 1 below shows the amount of CO_2 produced for a 500 ft. length of pipe. The emissions include the raw-material extraction and processing and pipe manufacturing factors.

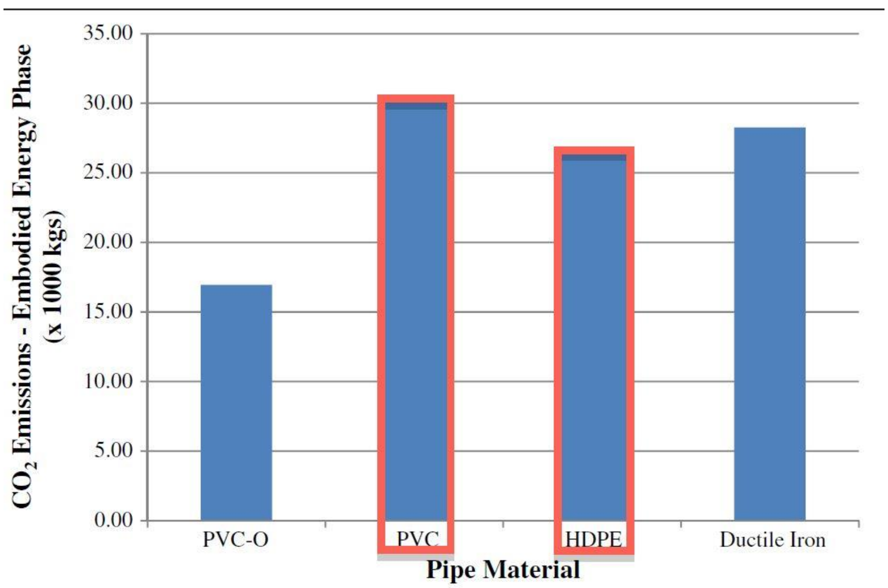

Figure 1: Production CO_2 emissions released in kilograms (x 1000).
Retrieved from (Piratla, Ariaratnam, & Cohen, 2012)

It is seen that purely from the extraction and manufacturing process, HDPE releases less CO_2 emissions than PVC. However, Dr. Piratla's additional tests discovered that through the entire lifecycle of HDPE (basing it on a lifetime of 50 years) it released slightly more CO_2 emissions than PVC (Piratla et al., 2012).

From his article it was apparent that it was released from what he considered as the 'usage phase'. This is illustrated in Figure 2.

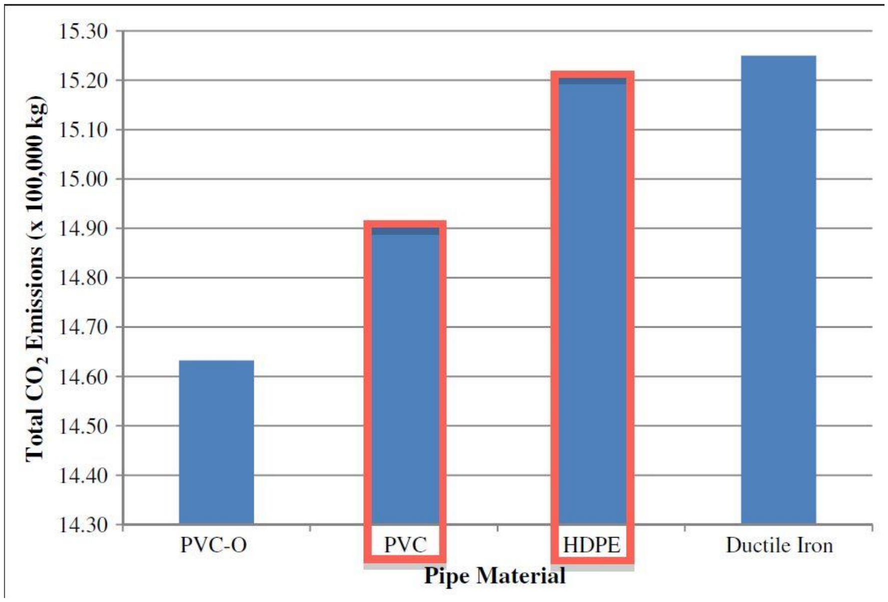

Figure 2: Total amount of CO2 expended in a lifecycle of 50 years (x 1000).
Retrieved from (Piratla et al., 2012)

The breakdown of greenhouse gases during PVC production can also be seen in Table 3 (units are kg of GHG per ton of PVC). According to Table 3, CO_2 is the predominant component of GHG emissions during PVC production. Since the demand of PVC is increasing (Lerner, 2010) and millions of tons of PVC are produced every year, the pollution associated with PVC production is very large.

Burden	Rigid PVC	Flexible PVC
CO_2	1,846	1,152
Dust	3.70	2.31
SO_2	12.34	7.71
NO_x	15.19	9.48
HCl	0.22	0.14

Table 3: Greenhouse gases produced from PVC production.
Retrieved from (Brown et al., 2000)

4.3 ENERGY CONSUMPTION

Table 4 below shows a breakdown of the total energy used for the same four plastics during a lifecycle of 50 years.

Life-cycle phase	PVC-O	PVC	HDPE	Ductile iron
Embodied energy	16,951.00	30,463.76	26,604.35	28,261.13
Pipe installation	2,830.40	2,830.40	2,830.40	2,830.40
Usage phase	1,442,866.99	1,457,143.65	1,491,287.74	1,493,177.70
Transportation	581.07	630.54	618.30	707.60
Total	1,463,229.45	1,491,068.35	1,521,340.78	1,524,976.83

Table 4: Total energy expended over a lifecycle of 50 years.
Retrieved from (Piratla et al., 2012)

The 'Embodied energy' row represents the total energy required to manufacture and extract the material. As discussed earlier, HDPE releases less CO_2; and therefore, utilizes less energy in the process. Dr. Piratla (2012) assumed it would require the same amount of energy to install all four drainage types for simplicity; however, there have been some cases where HDPE does not require as much equipment for installation as compared to PVC ("HDPE pipe gives contractors leak-proof flexibility", 1997). Since the construction equipment releases CO_2, the amount of energy may vary; thus, the total energy expended could fluctuate. The major difference in energy usage between HDPE and PVC is during the 'usage phase'. Dr. Piratla (2012) split this stage into three categories:

- Energy required to start the initial flow and set the correct pressure via pumps
- Maintenance of the pipes
- Repairs of the pipes

(Piratla et al., 2012)

It was stated that the energy associated with the second and third categories were similar, as PVC and HDPE have relatively the same life expectancies (Piratla et al., 2012). The main difference between the amounts of energy expended from HDPE versus PVC piping was mostly due to the initial pumping needed to set the pressure. The use of this pump releases large amounts of CO_2; and since HDPE is more sensitive to internal pressure than PVC, this phase releases significantly more CO_2 (see Appendix A). Figure 2 above summarizes this and shows the total amount of CO_2 expended by the four materials throughout the plastic's lifecycle.

4.4 ASPECTS OF RECYCLING HDPE AND PVC

Another factor that must be considered when evaluating the environmental impact is the amount of waste generated and how the waste can be disposed of. PVC cannot be readily recycled due to its chemical composition, whereas HDPE is very easily recyclable (Build It Green, 2006). Instead, PVC is disposed of by three commonly used methods: feedstock recycling, incineration, or in landfills (PVC, n.d., PVC recycling in Europe).

Feedstock recycling is a growing practice in PVC recycling, and European groups such as *Recovinyl* have set a goal of "recycling 800,000 tonnes [of PVC] by 2020" (recovinylPlus, 2013, VinylPlus & Recovinyl are gradually closing the loop, para. 1). Their progress can be seen in Table 5 below. Despite this effort, "82% of waste PVC goes to landfill[s], and 15% to incineration" (Brown et al., 2000, pp 3) every year. Therefore, environmental pollution produced by PVC is still prevalent and will continue to grow due to the practice of incineration and landfills.

Recovinyl registered recycled volumes per Country

Actual figures in tonnes	2005	2006	2007	2008	2009	2010	2011	2012
Austria	-	-	-	4,398	3,815	4,616	6,049	6,349
Belgium*	1,500	2,739	1,954	3,462	5,493	5,141	2,813	2,771
Czech Republic	-	-	1,165	5,858	13,685	16,464	13,288	14,902
Denmark	-	-	2,896	2,586	2,445	2,923	2,763	1,950
France	2,000**	7,446	13,276	16,943	10,89	17,377	17,317	26,346
Germany	-	5,522	35,927	77,313	71,081	92,242	91,200	136,796
Hungary	-	-	256	804	538	617	784	621
Italy	-	828	4,252	16,115	15,681	16,417	18,508	16,233
Netherlands	4,500	10,972	8,959	10,731	10,009	16,909	13,729	28,932
Poland	-	-	475	3,518	7,648	13,227	10,824	9,595
Portugal	-	-	-	477	903	1,437	1,489	3,047
Romania	-	-	-	-	-	27	807	1,647
Slovakia	-	-	-	-	994	1,959	697	481
Spain	-	2	-	6,293	9,093	14,838	22,131	23,075
Sweden	-	94	-	-	-	1,277	2,141	2,098
UK***	8,000	17,087	42,162	42,895	33,963	49,343	48,544	79,330
TOTAL	**16,000**	**44,690**	**111,322**	**191,393**	**186,238**	**254,814**	**253,086**	**354,173**

Table 5: Volume of PVC recycled from 2005 to 2012.
Retrieved from (vinylPlus, 2011)

Incineration is another option for disposing PVC once its lifecycle has ended. This involves burning the entire plastic and harvesting the heat energy to power communities; and so, municipal governments often oversee the process (PVC, n.d., Waste Management). Efforts are made to constrain gases that could act as pollutants; however, numerous amounts of dioxins are still released as can be seen in Table 6 (Brown et al., 2000; PVC, n.d., PVC recycling in Europe). Since incineration introduces large amounts of greenhouse gases into the atmosphere, it is not as an environmentally friendly option as feedstock recycling.

Incineration burdens	Units	Rigid PVC	Flexible PVC
Direct emissions to air			
CO_2	kg / tonne of waste	1393	1673
NO_x	kg / tonne of waste	1.01	1.01
SO_2	kg / tonne of waste		
HCl	kg / tonne of waste	0.051	0.051

Table 6: Greenhouse gases generated from PVC incineration.
Retrieved from (Brown et al., 2000)

The third alternative for PVC disposal is to discard the material in landfills. This method was predominant until the environmental effects were studied. However, the amount of PVC waste that is contributed into landfills each year is still substantial (see Table 6). From Table 7, 95% of construction waste, such as drainage piping, is buried in landfills which could lead to the leaching effects mentioned earlier.

Type of waste[a]	PVC waste (tonnes/a)	Landfilled portion (%)	Landfilled PVC waste (tonnes/a)
construction and demoliton waste	442,000	95	419,900
electrics and electronics waste	110,000	90	99,000
Packaging	796,000	70	557,200
automotive waste	120,000	80	96,000
Other waste	406,000	n/a	n/a
Total	1,874,000	65	1,218,100
MSW	1,147,000	70	802,900
Future MSW[b]	2,600,000	45	1,170,000

Table 7: Percentage of PVC wastes in landfills.
Retrieved from (Meriowsky, 2002)

The major disposal methods for PVC waste are not sustainable and cause a large production of pollution every year. This will persist until a larger movement is made towards feedstock recycling. Since HDPE is easily recyclable compared to PVC, investments into HDPE piping will have a more immediate effect on the protection of the environment (Build It Green, 2006).

4.5 ENVIRONMENTAL IMPACT SUMMARY

It was difficult to determine which material had the lowest negative environmental impact. The carbon emission totals show that HDPE releases slightly more CO_2 than PVC over a lifecycle, but less during production alone. However, HDPE has the ability to reduce emissions due to its easier installation process as mentioned in section 3.4. Additionally, green PVC recycling methods have not been fully adopted; thus, pollution produced during waste disposal is still significant. Therefore, it is unclear which plastic holds the larger repercussion.

5.0 ECONOMIC IMPACT

A significant factor that is inhibiting the further implementation of HDPE over PVC is the costs associated between the two plastics. Aspects that will be evaluated in the economic comparison will be the costs due to production and installation, a lifespan analysis and the economic concerns regarding recycling processes.

5.1 PRODUCTION COSTS

An economic factor that is essential in an analysis of a product is the cost of producing the material. This sets the retail value and thus the overall expense of the product. According to Klump (2013), "the PE industry will see a 28.7% boost to existing North American PE capacity...in the span of three years" (pp 34). Furthermore, as reported by Hydrogold Int'l Water Management Consultants (2012), the cost for the actual HDPE plastic is already currently cheaper than PVC plastic. With an increase in production, HDPE could possibly become an even cheaper resource to utilize (Klump, 2013). However, a downfall of HDPE is the fittings that are required. Although both PVC and HDPE need extremely accurate fittings, due to HDPE's complexity in material, the fittings cost more to produce (Hydrogold Int'l Water Management Consultants, 2012). The reason why the fittings are so expensive is because of the way HDPE is installed. Since it uses butt fusion welding, the fittings must be made to tolerate high temperatures; thus, they must be made with polypropylene, which is another type of plastic that contains a higher heat tolerance. However, these are much more costly and bulkier than PVC fittings. From figure 3, the bulkier polypropylene fitting, shown on the left side, costs $16 as opposed to the PVC fitting which costs $4 (Hydrogold Int'l Water Management Consultants, 2012). With an increase in production of HDPE, the fittings could possibly decrease in price; however, at the moment they are very expensive (Hydrogold Int'l Water Management Consultants, 2012).

Figure 3: HDPE fitting versus PVC fitting.
Retrieved from (Hydrogold Int'l Water Management Consultants, 2012)

Another key note is the lengths that each pipe is available in. Due to PVC's rigidity, it is restricted by the lengths that it can be produced in, whereas HDPE does not have this limitation due to its flexibility. Therefore, HDPE can be manufactured and delivered in longer lengths requiring fewer joints than PVC (Build It Green, 2006). Although the cost of the fittings is significantly higher for HDPE, since fewer of them are needed, the overall costs may balance.

PVC still remains a dominant leader in the plastic industry, mainly due to its slightly cheaper overall cost (pipe and fittings) and its long history in the business. As can be seen in Table 8, the current demand for PVC throughout the world is increasing. Despite HDPE being a suitable replacement for PVC, inevitably the global market determines whether it will be implemented.

PVC GLOBAL CAPACITY OVERVIEW ('000 TONNES)

Region	2008	2009	2010E	2011E	2012E	2013E	2014E
North America	8,338	8,042	8,118	8,592	8,592	8,592	8,592
South America	1,636	1,686	1,656	1,656	1,756	1,851	1,886
West Europe	6,896	6,974	6,889	6,819	6,819	6,819	6,819
Central Europe	1,445	1,483	1,483	1,603	1,603	1,603	1,603
CIS & Baltic States	629	629	653	953	953	1,283	1,283
Middle East	791	791	1,091	1,290	1,290	1,515	1,740
Africa	425	425	525	625	625	625	625
Indian Subcontinent	1,245	1,345	1,495	1,495	1,495	1,495	1,495
Northeast Asia (including China)	19,569	20,440	22,965	25,381	26,726	27,051	27,051
Southeast Asia	2,324	2,339	2,409	2,449	2,449	2,449	2,449
GLOBAL	43,298	44,154	47,284	50,863	52,308	53,283	53,543
Growth Rate	6.72%	1.98%	7.09%	7.57%	2.84%	1.86%	0.49%

Source: CMAI & JP Morgan

Table 8: Past and predicted demand of PVC
Retrieved from (Lerner, 2010)

5.2 INSTALLATION COSTS

A compelling factor for any new project, in addition to the material costs, is the installation costs. Since HDPE is relatively new to drainage applications, the choice of PVC was rarely questioned due to its low costs. However, as more tests are conducted on HDPE, the decision to implement PVC piping is not a straight-forward matter anymore. According to Appendix A, HDPE holds the lowest initial cost for installation as a result from the reasons discussed in section 3.4. Additionally, due to a difference in physical properties, mainly the flexibility that HDPE provides, contractors will sometimes use HDPE to lower material and installation costs ("HDPE pipe gives leak-proof flexibility", 1997). A proven success of this was accomplished near Calgary, Alberta where HDPE was chosen over PVC because the costs associated with materials and installations were reduced by almost 40% ("HDPE pipe gives leak-proof flexibility", 1997). The Villa Development and Construction Co. decided to implement HDPE as:

- HDPE's flexibility allowed less bends (fittings) to be used than a PVC pipe network
- HDPE's properties allowed less equipment for installation

- HDPE's tolerance to frost levels enabled a shallower trench to be utilized

("HDPE pipe gives leak-proof flexibility", 1997)

Since PVC is very stiff, any directional changes would require bends to connect the sections together. This could be avoided through the use of HDPE due to its flexibility. This same property enables less equipment to be used since it is easier for contractors to manipulate and install the pipe. With the "normal installation of PVC pipe…an excavator, a bulldozer and a packer [need] to continuously dig, backfill and compact the trench…" ("HDPE pipe gives leak-proof flexibility", 1997, pp 1) while HDPE "only requires such equipment at the very end of the job…" ("HDPE pipe gives leak-proof flexibility", 1997, pp 1). Finally, to avoid fracturing the pipe due to frost, usually drainage pipes are buried deeper into the ground. However, "…since the bend of HDPE is 25-30 times its diameter meaning it will not crack under freezing conditions – workers were able to bury it at a considerably shallower depth" ("HDPE pipe gives leak-proof flexibility", 1997, pp 1).

Furthermore, Tony Radoszewski, the executive director of the Plastics Pipe Institute (Midwest Contractor, 2007), stated that "corrugated high-density polyethylene (HDPE) pipe is proven to be a cost-effective solution for its ability to outlast and outperform alternative products…" (Midwest Contractor, 2007, pp 2). Both types of piping have proven to be leak-free and reliable, but the resilience incorporated in HDPE provides ease and efficiency during installation.

PVC is sometimes more desirable over HDPE as its rigidity and toughness can be altered by means of controlling the amount of plasticizer added during the production process (Lanxess, 2010). This enables PVC to be used in multiple types of drainage systems. Appendix A agrees with this and states that PVC is able to withstand greater amounts of internal pressures compared to HDPE. Due to this, HDPE is primarily used for gravity flow or low head pressure drainage systems. Appendix A also states, that PVC is known to degrade due to UV exposure. Due to this degradation, the life expectancy will decrease. HDPE, on the other hand, is UV resistant; therefore, this problem is not an issue in regards to HDPE installation.

5.3 LIFECYCLE OF HDPE VERSUS PVC

The initial cost is not the only aspect that should be assessed when deciding between HDPE and PVC. Long-term durability must also be evaluated to ensure the investment in the material is justified. According to Hydrogold Int'l Water Management Consultants (2012), since HDPE piping contains a thicker pipe wall and is more ductile than PVC, HDPE is more tolerant during the manufacturing process. Another effect from these properties is that HDPE is more tolerant to poor installation and will last much longer than PVC under the same conditions. Also, repairs can be immediately worked on with the use of HDPE. When PVC is installed with a Solvent Weld Joint, it can only be worked on 24 hours after pressurizing the joint (Hydrogold Int'l Water Management Consultants, 2012). Additionally, this method causes PVC to have a lower leak resistance compared to HDPE which may impact the long-term costs (Build It Green, 2006).

PVC and HDPE are very similar in strength and according to Pluimer (2007), there is no doubt that HDPE would not be able to withstand a similar duration to that of PVC. The lifespan of both HDPE and PVC is generally around 50 years (Hülsmann, May 2004). This is because the long-term effects of pressures on PVC and HDPE are relatively the same as shown from the Iowa formula which was described in Appendix A. Therefore, in proper installation conditions, PVC and HDPE have comparable lifespans.

5.4 ECONOMIC ASPECTS OF RECYCLING

The prices of each disposal method described in 4.4 vary, but landfills are generally the cheapest solution despite being environmentally hazardous (Brown et al., 2000). Brown (2000) and his colleagues estimated the cost of switching to a greener alternative in order to reduce pollution and dioxin release. His estimations are shown in Table 9.

4% discount rate	Scenario 1	Scenario 2	Scenario 3
Average total PVC waste diverted, million tonnes2000-2020	4.5 to recycling	9.76 to recycling	9.6-11.0 to landfill
From landfill	2.68-2.91	5.7-6.22	-
From incineration	1.60-1.83	3.55-4.07	9.6-11.0
Total costs, million €			
Excluding 'incinerator subsidy'	372 to 381	2,179 to 2,200	-203 to -235
Including 'incinerator subsidy'	199 to 230	1,839 to 1,903	-882 to –1,019
Annualised costs, million € / year			
Excluding 'incinerator subsidy'	27 to 28	160 to 162	-15 to -17
Including 'incinerator subsidy'	15 to 17	135 to 140	-65 to -75
Cost per tonne diverted € /tonne			
Excluding 'incinerator subsidy'	82 to 84	223 to 225	-21
Including 'incinerator subsidy'	44 to 51	188 to 194	-92

Table 9: Costs of Disposing PVC.
Retrieved from (Brown et al., 2000)

The scenarios illustrated in Table 9 are as follows:

1. Switching from incineration to recycling
2. Switching from landfill to recycling
3. Switching from incineration to landfill

(Brown et al., 2000)

Therefore, the cheapest solution according to Table 9 is switching to landfill from incineration and excluding an incinerator subsidy. This idea of switching also illustrates that the cheapest option for disposal of PVC is to disregard waste products in landfills.

HDPE can also be recycled according to Appendix A; however, the resins required for re-manufacturing recycled HDPE still need to be produced by post-industrial sources. Therefore, the amount of money saved does not differ by a large degree.

5.5 ECONOMIC IMPACT SUMMARY

HDPE has shown to be slightly more expensive than PVC depending on the situation. The total cost for the pipe and fittings is more expensive than PVC, however in specific conditions it has shown to reduce costs due to its flexibility properties. It is also more resilient than PVC so in the long-term, it may be beneficial to pay a little more since it could potentially last longer. Similar to the environmental impact, neither material is decisively dominant as both contain their downfalls. In a situation that needs more durability, HDPE is recommended as it could lower the lifecycle costs. However, PVC can be cheaply utilized in conditions that do not necessarily face these same circumstances.

6.0 CONCLUSION

Drainage lines make up a large portion of plastic uses; therefore, the plastic that is utilized is a major concern. PVC is the predominant leader in this industry; however, adverse side effects described throughout this report generate debate. The alternatives: ABS, Bio – Vinyl, and HDPE were first analyzed by means of primary research in order to determine which plastic was the best replacement for PVC piping. Out of these three options, HDPE was selected for the investigation.

By conducting the triple bottom line assessment, HDPE could be compared to PVC. HDPE had a greater net positive social impact than PVC due to its low emissions of toxic compounds, minimal health risks and greater ease in construction procedures. HDPE and PVC each had positive and negative environmental impacts. HDPE releases slightly more CO_2 than PVC over a lifecycle, but HDPE has the ability to reduce emissions due to its easier installation process. On the other hand, recycling methods for PVC are not practised enough to cause a decrease in PVC pollution generated from waste. Therefore, it was agreed that the environmental concerns for HDPE and PVC were equal. The economic aspect of the triple bottom line indicated that HDPE is slightly more expensive than PVC, although this varies depending on the situation. HDPE has a greater total cost for the pipe and fittings than PVC, however in specific conditions the cost is lower due to its flexibility properties. Similar to the environmental impact, neither material is decisively dominant as both contain their downfalls.

HDPE has clear benefits over PVC and due to its minimal social impacts regarding human health and its favorable properties such as flexibility and strength, this piping is recommended as an alternative to PVC drainage systems.

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APPENDICES:

APPENDIX A *–Email Conversation with Dan Currence, Director of Engineering for the Corrugated Plastic Pipe Association*

Specific questions regarding mechanical properties of PVC, ABS and HDPE were sent to the Plastic Pipe Institute along with inquiries on environmental impacts of all three plastics. The questions and answers are as follows:

1. How does PVC compare to HDPE and ABS for drainage systems? (life expectancy, maintenance costs, durability, etc.)

"HDPE is not as brittle as PVC, and HDPE is easier to handle than either PVC or ABS. HDPE, with its carbon black content, is more resistant to UV exposure than PVC & ABS. Properly handled and installed, the life-expectancy, durability, and maintenance cost would be similar…but, HDPE pipe has the lowest initial cost, especially in larger diameters."

2. There is a new company called Bio Vinyl that does not use phthalates in their piping (http://www.biovinyl.com/). From further research we found that the replacements to phthalates are bio-plasticizers which are derived from plants. Do you know anything regarding this new piping? If so, what can you tell us about it regarding life expectancy, long and short-term costs, impact on environment)

"I am not familiar with this new pipe."

3. HDPE is commonly used for bottles, containers etc. How different are the processes/chemicals used to process HDPE for those common purposes versus for drainage piping?

"There are a variety of differences between resins used to make consumer goods and those used for making HDPE pipe. You might want to research this more thoroughly on the internet at sites such as Formosa Plastics, http://www.fpcusa.com/pe/index.html. The resins used for making pipe are some of the highest densities among HDPE resins. As such, they are long chains of molecules with few branches, allowing the densities to be the highest (>0.96 g/cc). HDPE pipe is extruded, making melt indices critical. Most HDPE consumer products are blow molded or injection molded. The stress crack resistance properties for HDPE pipe that have been used for the past 13+ years are also unique. Though HDPE pipe could be made from post-consumer recycled HDPE products, more often those recycled resins must come from post-industrial sources in order to get to the highest densities and to have the most favorable stress crack resistance properties. Are there any harmful by-products? No. Also, are there any chemicals that leach off of HDPE like phthalates do in PVC? No"

4. People say that PVC should be used over HDPE because PVC can withstand a greater amount of pressure than HDPE, how do you feel the two compare? Is there a significant difference?

"I'll assume that you're asking specifically to compare and contrast PVC & HDPE pipe. PVC is a stiffer material than HDPE. Therefore if your question regarding "pressure" has to do with pipe stiffness, then yes, PVC pipe generally has greater pipe stiffness than HDPE. PVC pipe stiffness is typically 50 pii and greater. HDPE pipe stiffness is typically 50 pii and less. The value of pipe stiffness comes during the handling and installation processes. Once PVC and HDPE pipes have both been properly handled and installed, then the pipe stiffness differences play insignificant roles in long-term pipe performance. For example, when calculating pipe deflection using the Iowa Formula, the pipe stiffness and the soil stiffness are both factors in the denominator. Whether the pipe stiffness is 50 (PVC) or 20 (HDPE) makes very little difference in deflection knowing that the soil strength is 2000 psi or so. Therefore, pipe stiffness is not a reason to prefer PVC over HDPE. Now if by "pressure" you are referring to internal pressures, then I agree. HDPE pipe used in drainage applications are designed for gravity flow or low head pressures only. By contrast, PVC pipe can withstand greater internal pressures for drainage applications."

5. There have also been reports of the extreme strength of HDPE when compared to PVC. What do you feel would be more beneficial for drainage pipes, strength tolerance or pressure tolerance?

"Again, buried flexible pipes like HDPE and PVC pipe transfer the loads (Dead and Live Loads) above them to the surrounding soils. So properly installed in gravity flow or low head applications, both pipe materials will have tremendous durability and service life. The key differences between PVC pipe and HDPE pipe in drainage applications are:

Durability – PVC is more brittle than HDPE pipe so is more susceptible to damage during handling and installation. PVC is also more susceptible to UV degradation.

Ease of Handling – besides being less brittle, HDPE pipe is manufactured in standard 20' lengths

Cost – HDPE pipe is less costly than PVC pipe…especially in sizes >12" diameter

Chemical composition – Because chlorine is involved in PVC, HDPE pipe is a more environmentally friendly material during manufacturing and once installed."

6. One clear benefit is the flexibility HDPE provides that PVC does not. How does this affect strength/pressure tolerances?

"As previously stated, HDPE pipe has a lower pipe stiffness than PVC. Higher pipe stiffness makes handling and installation less critical; but PVC is so brittle that it can be more sensitive to handling particularly in cold temperatures. Once buried, the differences in pipe stiffness have almost no bearing on the long-term pipe performance since the loads are transferred to the soils around both PVC and HDPE."

7. Are any harmful by-products produced in ABS manufacturing?

"I do not know."

8. Is ABS piping typical used for large-scale drainage systems?

“I am not aware of ABS being used in these applications. If not, what is inhibiting it? Most likely it is cost.”

APPENDIX B – *In-person Interview with Dr. Frank Ko, Professor for UBC Material Engineering*

Dr. Frank Ko was very useful in our investigation into alternatives to PVC and the environmental damage PVC causes. He stated that due to PVC's long history in the market, construction companies are better associated with the installation process of PVC piping. The main reason why PVC is used more than other pipes, such as HDPE and ABS, is due to cost. Dr. Ko knew studies that indicated leaching of phthalates from PVC into drinking water that lead to contamination. He did not know Bio-Vinyl specifically, but he suspects that since it uses bio-plasticizers instead of phthalates that it will have a reduced environmental impact. Dr. Ko said that bio-plasticizers are produced from a specific acid harvested from plants such as corn. He stated that HDPE is used for medical equipment such as syringes and so he suspects that there is a smaller chance that chemicals leach from HDPE piping since the plastic is used in a hospital environment. He concluded that all pipes will have some sort of chemicals that will leach/enter the soil due to degradation. Out of the three options of alternatives: HDPE, ABS or Bio-Vinyl, Dr. Ko stated that HDPE is the best contender to PVC. He also instructed us to investigate the Polymer Handbook in order to find the physical properties of any plastic material.

APPENDIX C – *Telephone Interview with Jun'ichi Jensen, Senior Codes Administrator for Building and Safety Standards, Office of Housing and Construction Standards, BC Government*

We questioned Mr. Jensen to see whether or not PVC health risks are considered in the BC building code. He stated that the BC building code mainly focuses on the safety of the residents and the safety of neighbours/environment as a secondary objective. The 'safety' he referred to was more along the lines of ensuring that the piping in the buildings were installed correctly to prevent potential faults and fractures, rather than the risk of phthalates leaching into the water. He does not know if there are any plans to change the code regarding PVC. The BC building code is structured based on the national code center in Ottawa which bases their code from the CSA standards. Also, HDPE is code compliant with the BC building code if installed properly.

APPENDIX D – *Telephone Interview with Dr. Goran Fernlund, Associate Professor for UBC Material Engineering Department*

Dr. Fernlund's research focuses on the mechanical aspects of polymers and plastics. Therefore, he was unable to answer any of our questions regarding the environmental impacts of PVC or HDPE. He stated that HDPE is used for medical containers and fluid containers so this might indicate that HDPE does not leach chemicals since it is used in a hospital environment. He suspects that PVC and HDPE have the similar properties regarding durability and flexibility.

APPENDIX E – *Email Interview with Dr. Savvas Hatzikiriakos, Professor for UBC Chemical and Biological Engineering*

Questions regarding the environmental impacts of PVC and any information regarding phthalates or bio-plasticizers were forwarded to Dr. Hatzikiriakos. He was unable to answer our questions however, due to the fact the processes in the production of PVC vary between manufacturers. He stated that "production includes a number of additives, which are using during the manufacturing stage..processing aids, slip agents, thermal stabilizers, UV stabilizers etc..only [companies] know what they have put into their products."

APPENDIX F – *Email Conversation with Wanda Howe, Inquiries and Client Services Officer for the Canadian Centre for Occupational Health and Safety*

Inquiries regarding the standards associated with the phthalates present in PVC were sent to the CSA after learning from the BC Government that the BC building code is derived from these standards. They stated that "Health Canada has issued a Phthalates Regulation, SOR/2010-298, under the Canada Consumer Product Safety Act, regarding the maximum allowable amount of three types of phthalates in the PVC used in children toys or child care articles. The presence of certain phthalates in children toys was also banned by U.S and the European Union." There are no regulations or standards regarding the presence of phthalates in PVC piping for drainage or sewer applications due to the fact that most of the pipes used are hard, un-plasticized PVC.

They also stated that:

" The CSA "Thermoplastic nonpressure piping compendium", published as CSA B1800, contains the CSA series of standards B181 and B182 which include specifications that must be met by the pipes manufactured from PVC and used in drainage and sewer application. Both CSA B182.2-11, "PSM type polyvinylchloride (PVC) sewer pipe and fittings", and CSA B181.2-06 "Polyvinylchloride (PVC) and chlorinated polyvinylchloride (CPVC) drain, waste, and vent pipe and pipe fittings" do not contain any reference to the chemical constituents of the PVC but, under "General requirements", section 4.1.1, stipulate the following:

"PVC compounds shall

(a) Comply with cell classification 12454 or 14333, as specified in ASTM D 1784;

(b) Comply with the applicable requirements of Clause 4 of CSA B181.0;" "