Curriculum Units by Fellows of the National Initiative
2008 Volume VII: Urban Environmental Quality and Human Health: Conceiving a Sustainable Future

Life Cycle Analysis of an ordinary plastic water bottle

Curriculum Unit 08.07.06, published September 2008
by Jennifer B Esty

Objectives

The ninth grade integrated science curriculum spends an entire quarter of the year exploring polymers, including plastics, petroleum, petroleum products, and other carbon applications. This unit will be used to teach most of the topics in the second quarter of the year. The appendix at the end of this unit contains the relevant New Haven standards. As New Haven's science curriculum is based on the Connecticut state science curriculum, which is ultimately based on the national standards, many teachers will find a similar place for this unit in their curriculum.

This unit will cover the entire life cycle of an ordinary plastic bottle. Most ordinary plastic water bottles are made from polyethylene terephthalate, or PET plastic. PET bottles are normally marked with a number 1 inside the three arrow recycling symbol. Polyethylene terephthalate is also sometimes abbreviated as PETE in some older publications. I have chosen to explore PET bottles for two primary reasons. My students are all pregnant and parenting teenagers, who learn the regular curriculum while they are with us. PET bottles are a familiar part of their lives because they have been told to drink lots of water while they are pregnant. Many choose to bring water in these plastic bottles from home, so the bottles are a common site around the school. Additionally, PET, as a plastic, offers an excellent opportunity to explore the diverse topics we are expected to cover while maintaining continuity throughout the term.

The unit will follow the stages of the bottle's life cycle, modeled on the typical life cycle that one might see for a living organism. Each section of the curriculum contains a bit of background about the particular stage in the bottle's life cycle, some ideas for teaching the stage and most will contain a specific suggested classroom activity.

The unit will begin with an introduction, which is designed to show the students generally where we are going with the unit. The family history section will come next as a way to introduce students to the concept that humans have existed for thousands of years without plastic water bottles. This concept is important for my students as most of my students were born after the mass consumption of single serving plastic water bottles began. These first two sections are not really part of the life cycle of the bottle as they are not repeated in a recycling story, but they help to set the stage for the life cycle stages that follow. The conceptions phase of this unit is about the bottle design. The design of an object has a large impact on how easily the object may be reused or recycled at the end of its life, so this phase is really the beginning of the life cycle, as it largely determines the eventual fate of the bottle. The section on the birth of the bottle discusses how the chemicals that make up a bottle came to be and come together. Adolescence in a bottle, like in a human is the time when the character of the bottle is formed, in this case the physical processes that are used to transform the amorphous PET flakes or pellets into the bottle itself. Adulthood, and the working life of the bottle, follows, after which, seniority ensues. The discussion about seniority will focus on how bottles can be reused and if they really should be reused. Finally, death, and for the bottle, the possibility of an afterlife (or recycling if you like) are discussed, which brings back the ideas of the importance of design and possible alternatives, which were discussed at the very beginning of the unit.

Introduction

This unit will begin with an exercise to show where the unit is going. Specifically, the introductory exercise will show the students the cyclical nature of a life cycle so the students will be able to see how the beginning of the process becomes important at the end and, in fact, can become the next stage of the cycle after the end. In this exercise, they will explore the stages of a generic life cycle by looking at how they perceive the stages of life they see in the world around them. When I teach this part of the unit, I will probably use a graphic organizer which will have a circle divided into wedges. The girls will label each wedge with a difference stage of life. The girls will be asked to think about and write down what they want for their children at the particular stage in their children's lives. Then, using the same organizer, we will look at how each stage might be applied to the life of a bottle and the girls will be asked to write down what they think is happening to the bottle at each stage of the bottle's life. This exercise could easily be modified for non-pregnant students by asking what they have experienced and hope to experience in the various stages of life.

Family History

No currently extant species of animals came into existence spontaneously, and their ancestral history plays a large part in explaining why they form as they do. The situation is similar with plastic water bottles. For many thousands of years, humans have needed to carry water, yet we have existed and thrived without plastics, specifically without plastic water bottles. Humans have a long history of using natural resources to fashion water carrying and storage devices. For examples, humans have used natural materials like gourds, bark, wood, bamboo, grasses, reeds, and various animal parts to fashion water carrying and storage devices. Humans also have a long history of manufacturing water carrying and storage devices from materials like clay, glass, metal, wood, and leather. For this section of the unit, the students are expected to be able to answer three fundamental questions about water carrying and storage options other than plastics: What has been used? What could be used? Is this a better option than the plastic currently used? This is a fairly small section of the unit, so I do not expect to spend more than a day or two on it, but it is important background for some of the later projects. I will probably have the students think about the sort of utility that water bottles currently serve, which is background for the conception section of the unit, and have them think about how the needs currently served by the water bottle were met before the advent of plastics. The students will probably do some sort of quick project, possibly a web collage, answering the questions outlined above, which will allow them to store information from this section for later in the unit.

Conception

Bottle design considerations

Any major project begins with a design phase; designing a single serving water bottle is no different. Careful thought goes into how the bottle will be used, the size, the shape, the color and texture, the label, the closure, and other visible marketable features of the bottle. Most design considerations, however, seem to be about marketing the product. Unfortunately, the ultimate end of life scenario for the single serving water bottle does not seem to be given very much consideration these days. [1] The book Paper or Plastic makes a good case for the need to consider the ultimate destination of the product when the first design considerations are being made.

A polyethylene terephthalate bottle is typically made from several layers of plastics. Each layer serves a different function in the performance of the bottle. For example, the inside of the bottle, the part that is in contact with the liquid contained in the bottle, will typically be made from virgin PET, or PET that is made fresh for this purpose as opposed to being recycled. The central sections of the bottle may or may not be made from virgin PET and the label is frequently made from something other than PET like paper or poly vinyl chloride (PVC) film. Then, there is the consideration of the cap. The cap may be made from PET, but it will frequently also contain some sort of lining, frequently PVC, to keep water from seeping out if the bottle is turned upside down or laid on its side. This diversity of material going into a single bottle has a number of advantages, but it also causes a number of problems. Clearly the materials decisions serve a purpose, which is carefully considered, but the eventual impact of those design decisions do not seem to be given as careful a consideration. For example, when multiple types of plastic are combined in a single product, it becomes very difficult and sometimes impossible to recycle the product at the end of its life. Even if the different types of plastic are not fused together, separating the types of plastic can become an expensive undertaking. When plastics are not fully separated before they are recycled, the resulting product will not have the intended properties because of the contaminants introduced when the plastics were not properly separated. New products made from the recycled plastic materials will have unintended properties caused by the contaminants, which can cause product failure, such as the plastic cracking or being too soft, or safety problems from unintended leaching of contaminants into the new container's contents. The later issue is why most PET food containers are required to have a layer of virgin plastic in contact with the food.

A number of countries, particularly in Europe have passed legislation to encourage or require that the end of life of the product be considered at its beginning. *Paper or Plastic* goes into quite a bit of detail about some of these considerations. These end of life considerations will be the focus of our class discussions. A large focus of my teaching in this class, beyond the delivery of content, is to encourage my students to think about the consequences of their actions. The curriculum includes a segment about the human impact on the world around us, and the topic of the effects of design choices on the environment will fit into this part of the curriculum very nicely. I intend to have the students answer the question of why are end of life issues important considerations in the design phase of a product. The answers will likely come in the form of a persuasive writing assignment, which happens to fit into the English curriculum, and is also an important part of science, particularly when it comes to policy decisions.

Birth: the primordial ooze to the chemistry of bottle life

Most plastic bottles are made from products produced from natural gas and the distillates of petroleum. So, the story of the plastic bottle necessarily starts with petroleum and the distillation process. The US Department of energy has a good website explaining how fossil fuels form. [2] Many good Earth science textbooks will also have an explanation of fossil fuel formation. What follows is a brief version of the story of fossil fuel formation, followed by an explanation of distillation and concluded with a description of the chemistry involved in making PET. A very brief explanation of organic chemistry is also included for those of us who haven't had organic chemistry in a while. The primordial swamp to fossil fuels Life began on Earth several billion years ago, precisely how many billion years ago is still being debated, but it was probably between 3 and 4 billion years ago. A long time after life first began, plants began photosynthesizing, capturing sunlight and using the energy to transform carbon dioxide into carbon chains, which became sugars, starches, and plant fibers. Some of these plants formed the basis of a food chain which supported a variety of living organisms. As these plants and other living things died, they did not immediately decay. The normal, natural processes of decay allow carbon and other nutrients to be recycled back into an ecosystem. However, in the case of these plants and animals, there was little or no immediate decay. Instead the starches, sugars, and fibers from the plants and tissues from the animals that may have died with them, broke down slowly and the carbon was not cycled back into the ecosystems. Over time land formed on top of the dead organisms and began to compact them. Compaction causes both temperature and pressure to rise, which caused the carbon chains to change from being fibrous structures to being a fossil fuel. A similar change, although less extreme, can occur when plant matter, like veggies, are left in a pressure cooker for too long. The vegetables change from being crisp and fairly rigid, to being soft and gooey, although still identifiably vegetable. The formation of fossil fuels takes much more time, pressure and heat.

Different circumstances formed different types of fossil fuels. Today there are three major sources of fossil fuels: coal, crude oil, and natural gas. Coal was formed when swamps were buried. This formation is still happening in the early stages in peat bogs around the world today, which is why peat makes such a good fuel. Oil and natural gas formed when deceased organisms sank to the bottom of the ocean. The organic mater was slowly covered and compressed. More compression leads to smaller carbon chains, forming natural gas. Less compression allowed longer carbon chains to stay together, so crude oil was formed. Small pockets of oil and gas formed in sedimentary rock. Under pressure, the oil and gas were forced up through the fairly porous sedimentary rock. In some cases, the oil and natural gas simply seeps to the surface. In many cases, however, the oil or gas was stopped on the way to the surface by an impervious layer of rock, which trapped the fossil fuels and allowed larger deposits to build up. Wells are drilled through the impervious rock and oil and gas are pumped out of the deposits. This is where most of our oil and natural gas come from today.

Class activity: history of life on Earth

In New Haven geology is taught in both the eighth and ninth grades. In the ninth grade, geological cycles are not taught until after this unit, so we will probably do a short introduction to the subject during which we will discuss how the petroleum and natural gas are formed. There are a number of interesting activities which can be used to teach this topic. I will probably use one that is fairly short, however, because we will be studying this topic in depth later during the year. What I most want my students to get out of this activity is the idea that fossil fuels are formed over millions of years, which is why they are not readily renewable. However, many students, particularly in the ninth grade, do not have a good concept of what "millions of years ago" really means. This activity is designed to give the students some idea of the relative magnitude of the geological time scale.

The activity I intend to do with my students is a variation on an activity I came across several years ago, whose original author I have yet to identify. The students will be asked to trace their arm onto a piece of long paper, possibly a piece of brown paper towel. They may need a friend to help them with this activity. It is important that when the arm is traced, the hand is flat on the paper, so it can be traced as well. The arm and hand will form the basis of the geological time scale. The students will label the arm with geological events. So, the shoulder will be about 4.6 billion years ago, when the Earth was forming. The biceps will be about 3 billion years ago, when the first life was appearing. The elbow is about 2 billion years ago. The middle of the forearm is about 1 billion years ago. The base of the thumb is the beginning of the Cambrian period. The base of the fingers is about 250 million years ago, or about the end of the Permian period, so much of the oil, gas and coal formation happened during the time represented by the palm. The space between the base of the fingers and the third knuckle is when the dinosaurs lived. About 1/8 of an inch from the tip of the finger, the glaciers receded from Connecticut. About 1/200 of an inch from the tip of the finger, the pyramids in Egypt were being built. This activity might also be a good opportunity to introduce students to the logarithmic scale, too.

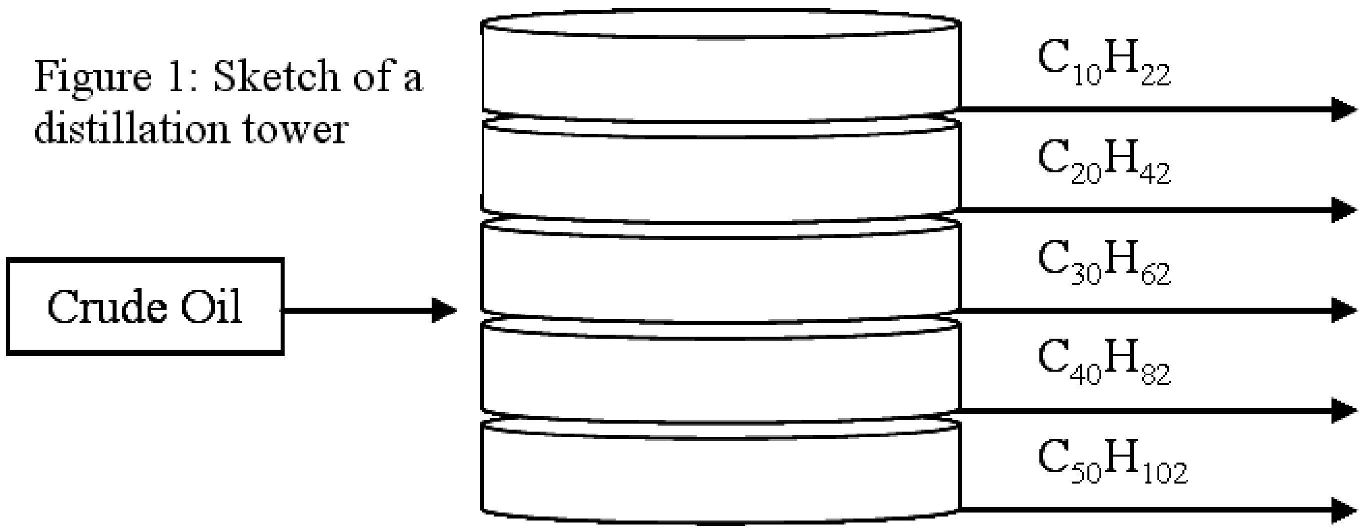
Petroleum cracking

Crude oil is the source of most of the chemicals used to make plastics. For some plastics, like polyethylene and polyethylene terephthalate, natural gas or methane can also be a source of component monomers. However, nearly all plastics use some form of petroleum distillate, like ethylene glycol at some point in their formation, and ethylene glycol is frequently used in PET production. [3] As noted above, crude oil is the remains of organic matter that lived many millions of years ago. Because it is formed from partially decayed or undecayed matter, the carbon chains have denatured and ended up in hydrocarbons of many different lengths. Petroleum cracking is the way that the different component parts, or the different hydrocarbon chains, are separated from the mess that is crude oil. I may do a demonstration here using different lengths of something like spaghetti to symbolize the different carbon chain lengths and have the girls try to sort the pasta by length.

At this point in the year, the class will already have discussed phase changes and will have done an experiment on evaporation and condensation; ideally, we will have done one making distilled water; at the very least we will have done an experiment boiling colored water and watching the steam condense on a cooler surface, like a mirror. At any rate, the students should have a fairly good understanding of the idea that liquids can evaporate and recondense, and that they condensate may be somewhat different from the original evaporated liquid.

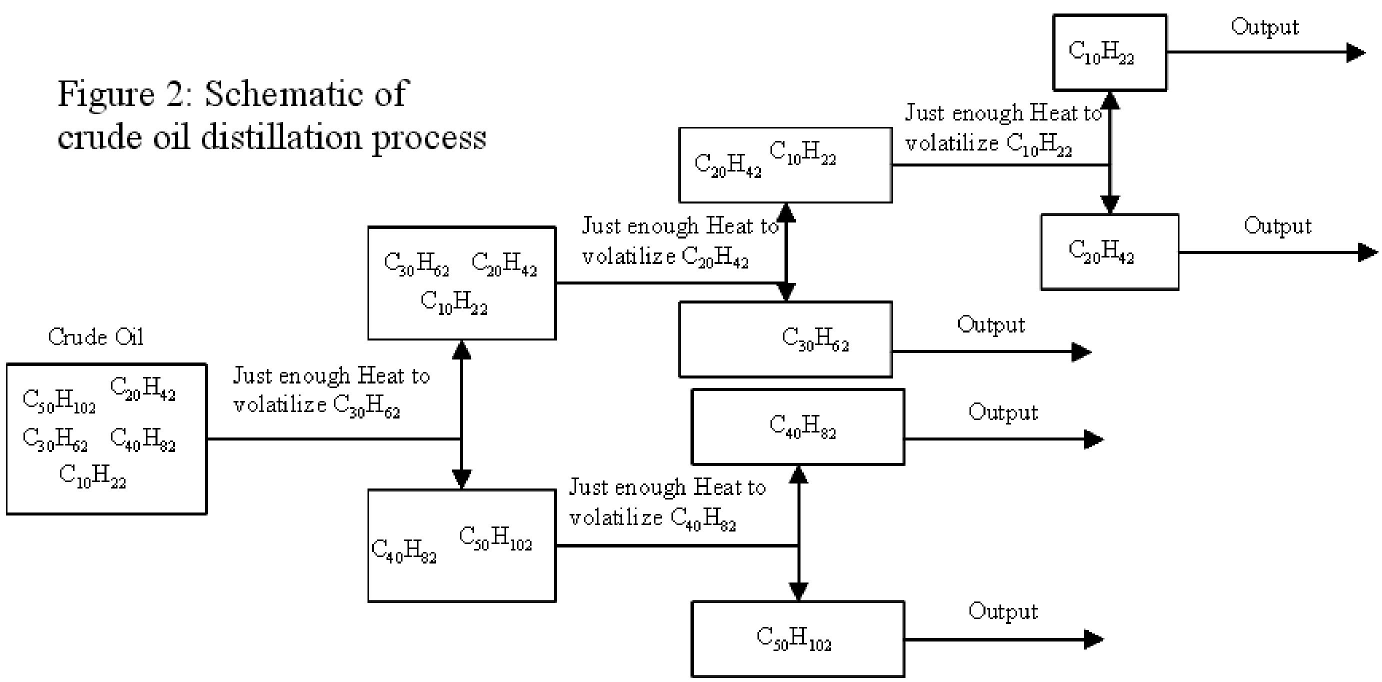
Petroleum cracking is based on the idea that every chemical volatilizes, or evaporates, at a different temperature. In the same way that grain alcohol is distilled from a fermented mash, petroleum distillates are distilled from crude oil. The primary difference is that when grain alcohol is distilled, there is generally only one particular distillate that the distiller is looking to capture; the rest is waste. In petroleum distillation, there are many compounds which the distillers wish to capture, so the distillation occurs using many different temperatures, rather than just one, as in alcohol distillation.

Figure 1: Sketch of a distillation tower



Crude oil is allowed to enter a distillation column. Heat is applied and some of the shorter polymer chains inherent in crude oil volatilize and rise up through the column until they meet a tray that is cool enough that they condense. The longer polymer chains are separated in a similar fashion further down the column. Each tray is at a different temperature, so different molecules will condense on it. From each tray, the condensate is removed and sometimes further refined, as needed. The heaviest, longer chains generally do not volatilize and remain as a liquid or solid, which is moved to another location. Figure 1 shows a schematic of a distillation column, with its trays. This is a very simplified version of a very complex process, so only a few of the compounds present in crude oil are shown. Figure 2 is a schematic showing the separation process that occurs in distillation towers.

Figure 2: Schematic of crude oil distillation process



Organic Chemistry

Organic chemistry is the study of molecules that contain carbon, generally large numbers of carbon atoms.

Like many scientific fields, it has a vocabulary and language of its own. Unlike many scientific fields, the vocabulary in organic chemistry, and plastics manufacture in particular, tends to be unique to the field, so it really requires some explanation before use. When I teach a subject which requires unusual vocabulary, I generally start with the vocabulary, so that we have a common language to use for discussions. What follows is a brief description of several terms that are commonly used in the plastics industry. When I teach this section, I will give the students the words on individual scraps of paper and the definitions on another and have the girls match the word with its definition. Many of these words have great potential for decoding activities, which I tend to use in my class. I find that students have a better chance at remembering words, if they can make a connection to some of the roots or other bits and pieces of the words.

- Monomer: a single molecule which can be linked to others of its kind to form a polymer.
- *Polymer*: a collection of monomers, generally in the form of a chain, although sometimes branching or forked. Polymers can be natural, synthetic, or synthetic derived from natural materials. Hair, proteins, cotton fiber, silk, wool, wood, and fur, are just a few examples of natural polymers. Rayon is an example of a synthetic polymer that is made from natural polymer materials. Nylon, polyester, bakelite, and high density polyethylene are examples of synthetic polymers.
- *Resin*: a collection of polymer molecules that have the potential to become a plastic.
- *Plastic*: a synthetic long chain synthetic polymer that has been formed or molded in some way. [4]
- *Plasticizer*: a chemical added to plastics polymers used to help the polymer chains slide past each other during the formation of the plastic and sometimes its subsequent life. Plasticizers act like ball bearings act in many mechanical applications, in that plasticizers unattached to the polymer molecules and allow the polymers to slide past each other. Like ball bearings, plasticizers are frequently not attached to the objects or molecules whose motion they are intended to ease.
- *Amorphous*: A solid state of plastics in which the polymers are tangled and disorganized, similar to spaghetti. [5]
- *Crystalline*: A solid state of plastics in which some of the polymers are organized and oriented in a similar direction. [6]
- *Thermoplastic*: A plastic which is solid at room temperature, can be heated, shaped, and cooled to create a desired shape. [7]
- *Condensation*: A polymerization reaction releasing water

Polymer formation begins with the addition of monomers to form small chains. Many monomers are actually gasses as the molecules tend to be very small and somewhat volatile. The small chains of monomers, called oligomers, are sometimes still gaseous and sometimes have begun to condense into a liquid. Most of the time, the initial reactions connecting monomers and oligomers require high pressure and/or high temperature because the proximity of gaseous molecules at normal pressure and temperature is not conducive to the frequent or rapid occurrence of reactions. Catalysts can sometimes be used at this stage, too. Once a fairly decent sized molecule has been formed as described, the polymer may continue to grow in one of several ways. In the natural world polymers like proteins are generally built by continuing to add one monomer at a time. Most high school biology text books will have a good description of how this happens. In the case of polyethylene terephthalate, monomers are joined using a condensation polymerization reaction when ethylene glycol is combined with terephthalic acid, producing PET and water. All synthetic polymers are made using one or more type of polymerization.

Classroom activity: making a polymer

I will have the students make a polymer, but I am not sure if we will be able to make an actual polymer because of chemical/pregnancy safety concerns. Failing the ability to make an actual polymer, or possibly in addition to or in preparation for making the polymer, the students will make a model of a polymer, possibly even PET. Regardless of how the polymer is actually made, I want the students to see the waste that is created when plastics are made.

Chemistry in a bottle

The life of a water bottle begins with the chemistry involved in making the plastic. Most water bottles, of the clear plastic type frequently sold in individual portions in the stores, are made primarily from polyethylene terephthalate, or PET (sometimes PETE). PET is a synthetic polymer made of repeating units of $C_{10}H_8O_4$. Figure 3 shows a diagram of the PET monomer. PET is generally made by the condensation polymerization ethylene glycol and either terephthalic acid or dimethyl terephthalate, creating a byproduct of either water or methane. Figure 4 shows where the water comes from in the condensation reaction between ethylene glycol and terephthalic acid. The diagrams shown in this section are intended for use both those who have a basic understanding of chemical equations. My students will have done some work with simple chemical equations by this point in the year, but they will probably require a bit more help to understand this section of the unit.

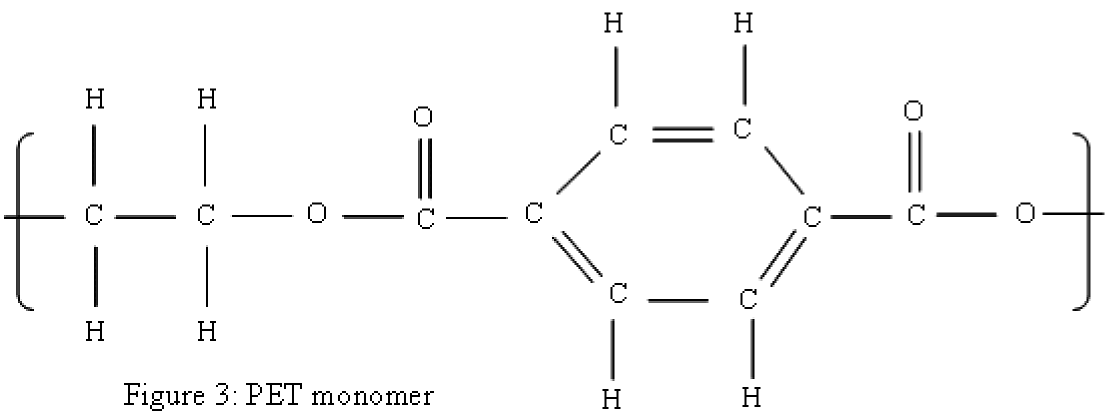
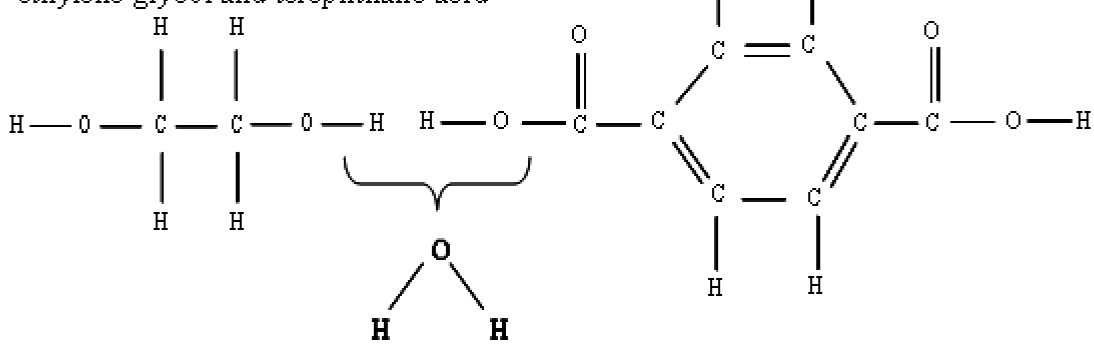


Figure 3: PET monomer

Figure 4: Condensation polymerization reaction of ethylene glycol and terephthalic acid



PET can be fairly rigid, which is inconvenient for most of its applications, so a plasticizer, di(2-ethylhexyl) phthalate or DEHP, among others is used to make it a bit more flexible. [8] Polymers, particularly long chains of polymers with some odd shapes sticking off them, get tangled easily. Think about a how easily a collection of computer cables can get tangled, and you will have some idea of what polymer chains can do. Plasticizers, as stated earlier, help the polymer chains to slide past each other and keep from tangling. The ease with which polymer chains slide past each other determines the final plastic's flexibility.

Class Activity: CAPT lab on physical properties of various plastics

This activity is one I am required to give some time before my students take their standardized test for the state in 10 th grade. The state asks questions on the standardized test about experimentation based on the series of experiments that the students do in the year and a half prior to the test. Since I have to teach the lab anyway and it seems to fit into this section of the unit, it seems like teaching it here is a good idea. The experiment may be found online at the link that is included in the resources section at the end of this unit. [9] In this experiment, the students are asked to examine several different types of plastics for tensile strength, puncture resistance, or abrasion resistance. Of the three, the first two are generally easiest to measure; however, with some creativity, the third can be measured as well. The teacher's version of this experiment may be helpful for those who have not done this experiment before.

Adolescence: or the formation of the physical character of the bottle [10]

Polyethylene terephthalate is a clear, semi rigid plastic with a structure that begins as an amorphous structure. As it is heated and formed, the crystals align to give the bottle its physical characteristics. PET is an interesting case study to use for studying plastics because it can be used to exhibit several different plastics forming techniques. Pet bottles are typically formed in a multi-step process. All PET bottles start as pellets or flakes of polyethylene terephthalate, either new or recycled or a bit of both. If additives like color or plasticizers are needed in the final product, an extruder is frequently used to mix the additives with the PET because most extruders are excellent mixers, too. If the product is extruded, it is reformed into pellets before being sent to the injection molding machine. Injection molding is the process used to make "preforms" for the stretch blow molding machine. The stretch blow molding machine forms the bottles into their final shape.

Extrusion and Injection molding

Extrusion and Injection molding are two techniques which are very commonly used in the manufacture of plastics. They are not, however, limited to use in the plastics industry. Metals, like aluminum and steel, are sometimes extruded, and ceramics are sometimes made using injection molding techniques. The following sections will describe in detail how these techniques are used to make PET bottles, but the ideas are far more widely applicable.

Extrusion

Extrusion is the process of forcing a substance through a holey piece, called a die, forming long strings of the substance. There are several extruders that are commonly used in the kitchen: a garlic press, a spaghetti maker, and a meat grinder are three examples of kitchen extruders.

In the process of forming a PET bottle, extruders are generally only used to mix ingredients before injection molding. However, the process is more commonly used in

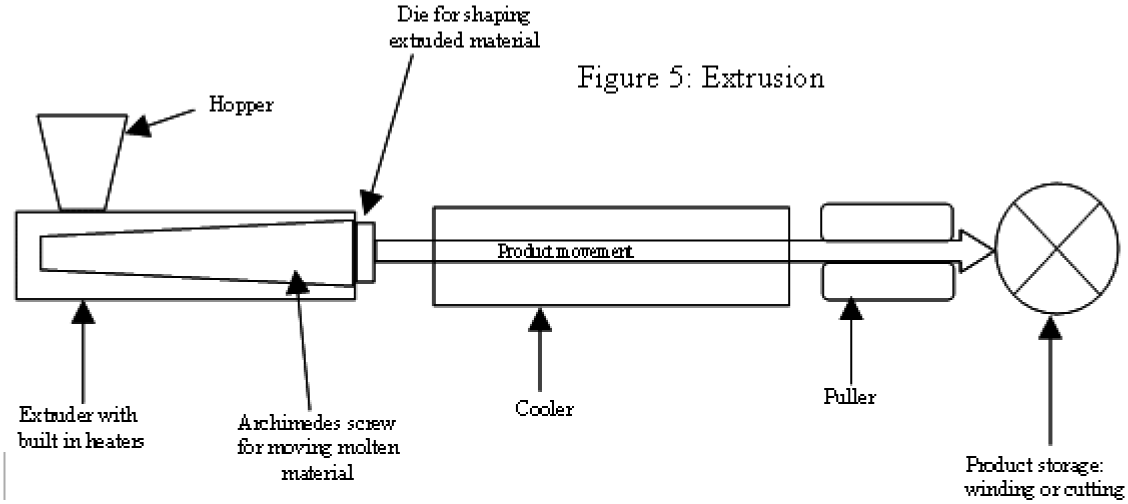


Figure 5: Extrusion

the formation of other synthetic polymers like PVC and in the formation of PET as fibers for clothing or carpet. The extruder has several component parts which are used in tandem to make the extruded plastic. The hopper is basically a giant funnel which feed pellets or flakes into the extruder. In the body of the extruder, there is a long Archimedes screw which through friction and additional heat melts and moves the product toward and through the die at the end. The die is a piece of metal with specifically shaped holes through which the product is forced, giving the product its shape. The product, then moves through a cooler, frequently water and on through a puller, which is like an old fashion wash wringer. Finally, the product is either cut to size or wrapped onto a storage device for later use. In the case of PET bottles, generally the product is cut from an extruded rod into pellets for later use in the injection molding machine. Figure 5 shows a generalized diagram of the process. [11] This process is good for making simple items that are continuous like pipes or yarn. It can also be used for simple shapes like pellets or cubes, but it does not work well for shapes that are more complex or require varying thicknesses in the final product.

Play-Doh makes several excellent extruders for use with its "modeling product", which I intend to use with my class. There is nothing quite like doing something to understand a process, and I firmly believe that any day my students get to play with play-doh is a good day in my class.

Injection molding

The injection molding process begins in a similar way to the extrusion process, but the final stages are quite different. Like extrusion, injection molding begins with pellets of flakes being fed into a long, heated tube. Injection molding machines can use either an Archimedes screw, like the extruder, or a ram, like a syringe. In either case, the molten plastic is moved to a reservoir until it is forced out through a nozzle into a mold. The plastic is cooled in the mold and released when the mold opens. In most cases, this process is nearly fully automated. Injection molding is used in cases where the product has a shape that is too complex for extrusion or requires less pressure than is experienced in an extruder. Injection molding is used in the water bottle process to make the preforms that are used in the stretch blow molding process, which is described in the next section.

In addition to making very fine extruders, play-doh also makes nice molds, so when my class explores the use of the extruder, we will also explore the uses of molds.

Stretch blow molding and bubblegum

Stretch blow molding is a variation on blow molding. Blow molding has been used to make glass bottles for many years. Essentially air is blown into a glob of molten material in a mold to create a hollow space inside a molded shape. When the material cools, it retains it hollow space and the molded shape. Stretch blow molding is a variation on blow molding where a piston or rod is used in conjunction with the air to cause the molten material to stretch along its axis as well as in the direction of its radius. Stretch blow molding is used to create PET bottles because the stretching in both directions helps the polymer chains line up and partially crystallize, which give the PET bottles superior strength in both the lateral and axial directions.

Pet bottles are formed when the "performs" are stretched in two directions to fit a mold. Bubble gum bubbles are a perfect analogy for stretch blow molding. If you have ever tried to blow a bubble without creating a preformed cavity in gum, you will know that it does not work very well. The tongue, the teeth and the lungs all have to work together to make a bubble. I am going to have the students blow bubbles into dixi cups or some other interesting mold so they get the feel of what it really means.

Adulthood: Or the working life of a bottle

Polyethylene terephthalate bottle are used primarily for soft drinks, including soda, juice, sports drinks, and water. Additionally, they are sometimes used for alcohol. Unfortunately, many of these contents dissolve the plasticizers that are used to make the PET flexible. The contents and the dissolved plasticizers are then consumed. There are several good resources for this section. They are listed together in the plastic uses section of the resources section at the end of this unit.

The primary concern with PET plastic is that the phthalates which are used as plasticizers are not chemically bound to the plastic and leach out under normal operating conditions for the bottles. According to BoÅ¡nir, et al, DEHP and DBP can and do leach into bottled water from the bottles under normal operating conditions. The State of New Jersey also found problems with some bottled water, and banned three bottled water manufacturers from selling bottled water in the state because their water contained levels of DEHP above New Jersey's 6 ppb limit. [12]

Although the amount of phthalate leaching into the bottles' contents is small, most of these chemicals appear to show endocrine disrupting tendencies even at very low levels. These endocrine disrupters can cause birth defects and may be carcinogenic. Many governments, particularly in Europe, have banned the use of many phthalates because of the perceived danger Specifically, according to the US "department of health and human services, DEHP may reasonably be anticipated to be a human carcinogen." [13] . As of this writing, both the US house and Senate have passed or agreed to the bill HR 4040, which in section 108 declares "it shall be unlawful for any person to manufacture for sale, offer for sale, distribute in commerce, or import into the United States any children's toy or child care article that contains concentrations of more than 0.1 percent of di-(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), or benzyl butyl phthalate (BBP)". Additionally, the bill provides further provision for the prohibition of "any children's toy that can be placed in a child's mouth or child care article that contains concentrations of more than 0.1 percent of diisononyl phthalate (DINP), diisodecyl phthalate (DIDP), or di-n-octyl phthalate (DnOP)" until the passage of a final rule based on the study of Chronic Hazard Advisory Panel. [14] More information on how endocrine disrupters cause health problems in humans can be found in *Plastics that may be harmful to children and reproductive health* and in *Generations at Risk*.

All of this is before one considers the water within the bottles, which according to the New Jersey report is frequently problematic as well.

Class activity: Science Technology, and Society CAPT lab on Plastics

The class activity for this section will be a lab I am required to do with my students. [15] It fits in nicely here because the students are asked to look at how plastics are used in the world and consider their benefits versus their risks. It goes a bit beyond the scope of this unit because the students are expected to explore plastics beyond just PET. I expect that my students will specifically explore the costs and benefits of PET and of Polycarbonate, which has been used to make baby bottles. They will probably also do some exploration beyond these two plastics.

Seniority: or the many reasons not to reuse a bottle

This phase will discuss how bottles are reused and the hazards therein. This section was my original motivating factor in choosing to take this seminar. My students are very good about reusing their plastic water bottles, but it may not actually be such a good idea. In this section, we will use the results from the prior section, adulthood, to delve deeper into the risks and benefits of reusing plastic water bottles. I think a debate on the issue for the whole school might be a good idea. Students will also be expected to present some alternate suggestions to plastic water bottles in their debate. This is where they will return to the information they gained in the first section, family history. The students will use what they have learned about alternatives, from the family history section and the information on the risks and benefits of using plastics to debate the benefits versus the costs of using PET bottled water. The entire school will be able to benefit from the information as most of our students use PET bottles for drinking water.

Death and Afterlife: Recycling?

In this section we will discuss the ultimate fate of the plastic bottles. This will also involve a project requiring that the students come up with creative ways to keep bottles out of the waste stream. At the moment I am thinking that might include everything from not buying the bottles to creative uses/recycled art projects for the bottles of a more permanent nature. This stage should also include a summary of the costs (primarily economic and environmental) of the production and disposal of the bottles. Our art teacher has been very successful in having her students do projects using found materials, which might be a good application. However, I would like to see the students do a project showing how to keep plastic out of the waste stream.

Recycling polyethylene terephthalate

An amazing array of technologies have evolved for the separation and processing of plastics. After the issue of finding a market for recycled plastics, the major issue with recycling plastics is sorting and separating plastic resins so that they may be reprocessed into new forms. The technology that has evolved for this purpose is a fascinating subject all by itself. The process of recycling can really be said to start in the birth and adolescent phases of the bottle's life. The more parts and materials that are added to the bottle, the harder it is to recycle the bottle at the end of its useful life. *Paper or Plastic* is a very good resource for looking at how design decisions can influence the ultimate end of a packaging material. Daniel Imhoff has included a number of very interesting case studies illustrating the benefits of considering the entire life cycle of a product in the design phases of packaging production. The PET industry has put together a very interesting collection of best practices for recycling PET, which describes much of the information found below. [16]

Recycled PET has a number of uses. Since 1991 100% recycled PET has been used in quart and pint sized plastic containers for fresh fruits and vegetables. Since 1992 recycled PET has been used in the clamshell packages for bakery and deli goods with a layer of virgin PET coating laminated on to the food contact surfaces. Since 1993 recycled PET has sometimes formed the center of a "sandwich" of laminated layers used to make soft drink bottles with a layer of virgin PET lining the food contact surface of the bottle. In 1994 a soft drink bottle was allowed which contains 100% recycled PET. Additionally, recycled PET is used to make thermoforming sheets and films for blister packs, and hard plastic laundry scoops; shipping strapping for boxes; engineered resins for use in cars; and fiber for fleece, carpeting, and quilted material applications. [17] However, in order to be reused, PET must first be collects, sorted, and cleaned.

Collection

Once plastics have been used to the extent of their useful life, some plastics will be recycled. As discussed earlier, some plastics are more easily recycled than others. However, any plastic that is going to be recycled must be collected and brought to a central processing facility. In the case of PET this is done in several ways. PET is unusual in that many states have deposit laws which require stores to reclaim some or all PET soft drink bottles that they sell. The PET bottles, like soda bottles, which go into the redemption machines found in many states, yield a high purity recyclable material stream for the plastic recycling industry. However, not all states have mandatory redemption laws and not all PET bottles go through the grocery story redemption process. This means that the bottle must be collected in another way. The other two most common collection methods are curbside recycling and drop-off centers or transfer stations. The PET best practices document also mentions buy-back centers, but I have never seen one available to ordinary consumers, although they may be more common in other parts of the country. [18] Once the plastic is collected, it is generally sold to a plastics recovery facility of some sort; there are various types with minor variations in the work that they do, which are not largely relevant to this unit. However, if you are interested, I recommend reading the best practices document mentioned above.

Sorting [19]

Sorting plastics can be done either manually, automatically, or manually and automatically. The method used depends on the source of plastic coming into the plastics facility, the cost of running different types of sorting machinery, and the needs or requirements of the used plastics consumer. In nearly all cases, incoming plastics will pass over a screen where loose debris is separated from the plastics. From there, the plastic containers will generally pass to a conveyer belt system and through the sorting process.

Manual sorting may be divided into two categories. Positive sorting is when the desired plastics, PET in this case, are taken off the conveyer belt and sorted onto another belt or into a hopper. This is like taking your own luggage off the baggage carousel at the airport. Negative sorting is when the desired bottle is left on the belt and undesirables are taken off the belt. Positive sorting is most commonly done when the input stream contains many types of plastics and typically results in a fairly pure stream of the desired plastics. Negative sorting is more common when the incoming stream is more homogenous and can result in a less pure stream when more varied plastics are used as the input. Occasionally, ultraviolet light is used to help separate PET plastics from PVC plastics because PET bottle tend to fluoresce blue in UV light while PVC bottles tend to fluoresce yellow or green in UV light. However, as this does not always hold true, for various reasons, it is not a foolproof technique, and it exposes workers to ultraviolet light, which sunscreen manufacturers will remind you causes sunburn.

Automated sorting systems almost always involve light and typically fall into three categories: optical sorting by color, optical sorting by electromagnetic transmission, and optical sorting by electromagnetic reflection or fluorescence. The electromagnetic energy used in the automated sorting machines is generally either near-infrared light, visible light, or x-rays. Visible light optical sorting machines are frequently used to sort out colored plastics from clear ones. X-ray transmission mechanisms pass x-rays through the bottle material to a sensor on the other side. A computer processes the amount of light that comes through the bottle to see if any radiation was absorbed by chlorine atoms, which would indicated that the plastic is PVC. X-ray reflection machines measure the amount of x-ray radiation bouncing back from the plastic, again to determine if any chlorine atoms are present, which would indicate that the plastic is PVC. Near infrared light transmission mechanisms shine a beam of light through the bottle and analyze the light that passes through the bottle. Every substance absorbs light slightly differently, so the computer is able to tell which type of bottle is being examined by the light which is able to pass through, or not be absorbed, by the bottle. The machine, then sorts the bottle according to its composition. The bottles are then either bailed or ground into small pieces called dirty flake.

Cleaning

Sometimes bottles will come to a processing facility already ground into pieces called dirty flakes. This is more common in cases where the bottles were fairly homogenous to begin with, like soda bottles coming out of a redemption machine at the grocery store. In other cases, the bottles have come from an initial sorting facility and have been ground into dirty flake for sale. In either case, the flakes must be cleaned before they can be reused.

Cleaning generally starts with a blast of fresh air. In the same way that wheat and chaff may be separated by a breeze blowing through the threshed grain, lighter bits of paper and undesirable tiny bits of plastic (fines), dust, dirt and other impurities can be separated from the desired flaked of PET. The PET flakes, then, take a bath in a detergent which removes further dirt, glue, labels and other nasty things stuck to the bottle pieces. The cleaned pieces are allowed to settle to the bottom while other plastics and bits of labels float on the surface. This step is sometimes done in a centrifuge instead. The flakes are allowed to dry and sometimes are passes through an electrostatic separator to remove bits of metal which are sometimes present in recycled tennis ball containers. If the flakes were not very pure coming into the facility or if the customer requires extremely pure product, the cleaned flakes are sometimes passed through one of the automated sorting machines described above. [20] The clean, dried flakes are turned into the pellets described in the birth section above and can be used alone or with virgin PET to make new materials.

Class Activity

There are a number of possible classroom activities which could be used with this section of the unit. In my classroom, I will have my students do a project on keeping plastics out of the waste stream. As mentioned above, our art teacher is very good at having her students do projects using found pieces. I plan to have my students do some art work in a similar fashion using found plastics, either to show how plastics can be recycled and kept out of the waste stream or to show how plastics can be kept out of the waste stream by making them into pieces of art.

However, there are a number of other approaches to the topic. For example, students could do an interdisciplinary project lobbying a legislature to reduce the toxins in plastics used for foods. Students could do a project exploring what happens to plastic waste in their own community. Students could do a project aimed at increasing the recycling rate in their community or simply starting a recycling program in their own school. There are a number of resources in the next section which may be helpful for implementing these types of classroom activities. Be Creative!

Resources

Plastics processing

Anonymous, "Recycling Roundup: Everything you wanted to know about #1 and #2" *Pollution Prevention View* 8. 1 (2008), 4-5, http://www.ct.gov/dep/lib/dep/p2/newsletter/p2viewwinter08.pdf. (accessed July 2008). Basic information on how two types of plastics are recycled. Includes some nice links, too.

Fossil Energy Office of Communications, "Fossil Energy: How Fossil Fuels were Formed." March 25, 2008.http://fossil.energy.gov/education/energylessons/coal/gen_howformed.html (accessed July 2008). Good explanation of how fossil fuels were formed. Some dysfunctional links, though.

Hurd, David J. "Best Practices and Industry Standards." 1997.http://www.napcor.com/pdf/Master.pdf (accessed 7/11/08). This is an industry document, which is a very good basic explanation of how plastics are recycled. However, it should be noted that industry practices in this area have probably evolved some since it was written.

Imhoff, Daniel. *Paper or Plastic: Searching for Solutions to an Overpackaged World.* San Francisco: Sierra Club Books, 2005. This book is an interesting look at how and why packaging decisions are made and their consequences.

Strong, A. Brent. *Plastics: Materials and Processing.* 3 ed. Upper Saddle River, NJ: Pearson/Prentice Hall, 2006. Excellent primer on making industrial plastics.

Chemical Migration

Bosnir, Jasna, Dinko Puntaric, Antonija Garlic, Ivo Skes, Tomislav Dijanic, Maja Klaric, Matijana Grqic, Mario Curkovic, and Zdenko Smit. "Migration of Phthalates from Plastic containers into Soft Drinks and mineral Water." *Food Technology and Biotechnology* 45, no. 1 (2007): 91-95. Very nice paper on the chemical migration of phthalates from PET into various soft drinks and waters.

Wargo, John. *Plastics that may be harmful to children and reproductive health.* Linda Wargo, Nancy Alderman, Susan Addiss, Jane M Bradley. North Haven, CT: Environment and Human Health, Inc., 2008. Excellent explanation of why plastics pose a threat to human health.

Wargo, John. *Green Intelligences.* New Haven, CT: Yale University Press, 2008. This is going to be a great book; can't wait to read the full version.

Endocrine disruption

Schettler, Ted, Gina Solomon, Maria Valenti, and Annette Huddle. *Generations at Risk: Reproductive Health and the Environment*. Cambridge, MA: The MIT Press, 1999. Good book describing how environmental pollutant can cause human health problems.

Plastics Use

American Chemistry Council, "Plastics division." 2008.http://www.americanchemistry.com/plastics/ (accessed July 2008). Current information on Plastics from one of the major industrial groups.

Connecticut State Department of Education, "Science curriculum Embedded Tasks (Strand II)." 2002.http://www.sde.ct.gov/sde/cwp/view.asp?a=2618&q=320892 (accessed July 2008). The Strand II experiments are the ones that are included in this unit.

Environmental Working group, "Guide to baby safe bottles and formula." 2008.http://www.ewg.org/files/EWG_babyguide.pdf (accessed July 2008). Very useful for pregnant students.

FDA Center for Food Safety and Applied Nutrition, "Food Ingredients and Packaging." June 25, 2008.http://www.cfsan.fda.gov/%7Edms/opa-notf.html (accessed July 2008). FDA regulations on what packing materials can come into contact with foods. (Bottom of the page)

Jeavans, Christine. "A Month without Plastic." August 1, 2008.http://news.bbc.co.uk/2/hi/uk_news/magazine/7508321.stm (accessed August 2008). Journalist documents attempt to live for one month without plastic. Good for information on how plastics are used in daily life.

Packaging Today, "Packaging News for Packaging Companies,." 2008.http://www.packagingtoday.com/ (accessed July 2008). Information on current topics in plastics packaging as well as other sorts of packaging from the packaging industry.

Shukman, David. " Warning on plastic's toxic threat." March 27, 2008.http://news.bbc.co.uk/2/hi/science/nature/7316441.stm (accessed July 2008). Website describes the environmental persistence of plastics.

Society of the Plastics Industry, "The Society of the Plastics Industry." 2005.http://www.plasticsindustry.org/ (accessed July 2008). Current information on plastics from one of the major industrial groups

US House and Senate. (2008). *Consumer Product Safety Improvement Act of 2008* (HR 4040 (101st congress)). Washington, DC: US Government. This bill permanently bans the use of several phthalates in children's toys and temporarily bans the use of several others.

Bottled Water

Anonymous, " Mario Batali Gives Bottled Water the Boot." 2007.http://www.earthlab.com/articles/MarioBatali.aspx (accessed July 2008). Article about various restaurants choosing not to serve bottled water and some of their reasons.

May, Lindsay. "But It's Just a Bottle of Water…." 2006.http://www.sciencecases.org/bottled_water/bottled_water.asp (accessed July 2008). Case Study exercise on bottled water.

New Jersey Department of Health and Senior services. (2007). *Report to the New Jersey Legislature Senate Environmental and*

Assembly Environmental committees summarizing laboratory test results on the quality of bottled drinking water for the period January 1, 2006 through December 31, 2006 Trenton, NJ: State of New Jersey. Interesting information on water quality found in New Jersey's bottled water.

Information on the waste stream

Amaral, Kimberly. "Plastics in our oceans." unknown date.http://www.whoi.edu/science/B/people/kamaral/plasticsarticle.html (accessed July 2008). Describes how plastics end up in our oceans.

Amos, John M. "Cleaning Up the Waste Stream: Recycling Plastics." October 1993.http://extension.missouri.edu/explore/wasteman/wm0002.htm (accessed July 2008). Part of one of the CAPT experiments

Coalition for a safe and healthy Connecticut, "Coalition for a safe and healthy Connecticut." 2008.http://www.safehealthyct.org/welcome1.html (accessed July 2008). Connecticut group working to reduce the use of toxic chemical.

Connecticut Department of Environmental Protection, "Pollution Prevention View Magazine." 2008.http://www.ct.gov/dep/cwp/view.asp?a=2708&q=324064&depNav_GID=1763#CurrentandPreviousIssues (accessed July 2008). Magazine on Pollution Prevention published by the CT DEP. Good for student reading, approximately 6 th grade reading level.

Northeast Recycling Council, "Toxics in Packaging clearinghouse." 2007.http://www.toxicsinpackaging.org/index.html (accessed July 2008). Provides a model for legislation on reducing toxins in the waste stream.

Northeast Recycling Council, "Northeast Recycling Council." 2008.http://www.nerc.org/index.html (accessed July 2008). NERC's homepage: full of interesting ideas for recycling and accompanying legislation.

Appendix: New Haven Science Standards

Properties of Matter - How does the structure of matter affect the properties and uses of materials?

9.5 - Due to its unique chemical structure, carbon forms many organic and inorganic compounds.

> - Carbon atoms can bond to one another in chains, rings and branching networks to form a variety of structures, including fossil fuels, synthetic polymers and the large molecules of life.

Science and Technology in Society - How do science and technology affect the quality of our lives?

9.6 - Chemical technologies present both risks and benefits to the health and well-being of humans, plants and animals.

- Materials produced from the cracking of petroleum are the starting points for the production of many synthetic compounds.
- The products of chemical technologies include synthetic fibers, pharmaceuticals, plastics and fuels.

D 17. Explain how the chemical structure of polymers affects their physical properties.

D 13. Explain how the structure of the carbon atom affects the type of bonds it forms in organic and inorganic molecules.

D 14. Describe combustion reactions of hydrocarbons and their resulting by-products.

D 15. Explain the general formation and structure of carbon-based polymers, including synthetic polymers, such as polyethylene, and biopolymers, such as carbohydrate.

D 16. Explain how simple chemical monomers can be combined to create linear, branched and/or cross-linked polymers.

End Notes

---

1. Imhoff , Paper or plastic

2. http://fossil.energy.gov/education/energylessons/coal/gen_howformed.html

3. ATSDR Toxicological Profile of Ethylene Glycol

4. Strong, Plastics, 5

5. Strong, Plastics, 75

6. Strong, Plastics, 75

7. Strong, Plastics, ch 7 and 8

8. Dimethyl phthalate (DMP), Diethyl phthalate (DEP), Dibutyl phthalate (DBP), and Dioctyl phthalate (DOP) are also used in PET. BoÅ¡nir, et al.

9. The student version of the experiment may be found here: http://www.sde.ct.gov/sde/lib/sde/word_docs/curriculum/science/strand2studentlaboratorymaterials.doc. The teacher version of the lab may be found here: http://www.sde.ct.gov/sde/lib/sde/word_docs/curriculum/science/strand2teacherlaboratorymaterials.doc

10. The information in this section comes predominantly from Plastics, Chapters 11, 12 and 13.

11. Information in this diagram came from *Plastics.*

12. New Jersey Report on Bottled water, pg 12

13. ATSDR Toxological profile for DEHP, Chapter 1, page 4

14. HR 4040 from the 101st congress. As of this writing this bill, the Consumer Product Safety Improvement Act of 2008, is not yet law.

15. The student version of this activity may be found here: http://www.sde.ct.gov/sde/lib/sde/word_docs/curriculum/science/strand2stspolymerstudentmaterials.doc. The teacher version of the

lab is here: http://www.sde.ct.gov/sde/lib/sde/word_docs/curriculum/science/strand2stspolymerteachermaterials.doc

16. Hurd 1997

17. Hurd 1997, 4

18. Hurd 1997, 10-15

19. Hurd 1997, 31-40

20. Hurd 1997, 17-21