



Polymer Composite Gasoline Tanks

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Introduction

The ultimate goal of this project was to produce profitable and quality polymer gasoline tanks and propose a competitive and appealing business plan.

In order to accomplish our goal, there are many factors and considerations that had to be evaluated in order to effectively produce polymer gas tanks. The following list shows the major factors of this project.

- Current Gas Tanks
- Safety and Regulations
- Material Selection
- Process Design
- Tank Design
- Financial Evaluations
- Risk and Uncertainty

The first task was to examine current gasoline tanks. Current tanks were examined in order to develop a launching point for the project. The gasoline tanks produced must be an improvement upon current tanks in order for them to be marketable. Existing gas tanks are made either of plastic or metal, which is typically steel. Steel has been the historical material for gas tanks. The plastic may be any type of material that meets the design criteria due to the various types of plastic available. Various materials were analyzed in order to meet the performance of current gas tanks.

Certain regulations must be adhered to in order to make a gas tank suitable for use in consumer automobiles and to place it in the market. In addition to the safety regulations, emissions standards must also be met. These two regulations identify two properties that must be considered: strength and diffusion. These two properties will be used to help examine potential materials for use in a gas tank.

The material used to construct the gas tank plays a major role in the in the physical characteristics and the economic feasibility of the polymer gas tank manufacturing process. The tanks had to be strong and resistant to diffusion as well as inexpensive so that the process was profitable.

Another major factor was the manufacturing process. Several processes capable of producing polymer tanks, each with respective advantages and disadvantages, were examined. Once examined, both the optimum process and material for polymer tank production were determined. The financial evaluation of each process was performed in order to compare the profitability of each process. The selection of the optimum material and process is discussed in the following report.

The gas tank and process designs are explained in detail. Finally, the business plan for the manufacture and sale of polymer gas tanks was created. It includes our future goals, optimal location, strategy, and the risk involved with this project.

Design Procedure

The design was carried out in several stages. The first stage was to examine current gasoline tanks and to investigate safety and emission regulations. Information on current gas tanks was obtained for several reasons. First, it served as a reference point for the project and provided ideas and opportunities to produce gas tanks superior to those currently in the market. The amount of competition for introducing a new tank was also needed. The safety and emission regulations were investigated and identified. The gas tank designed had to meet or surpass all of the regulations in order for the tank to be suitable for use in consumer automobiles.

The second stage of the design procedure was to identify potential materials. The materials were identified based on their properties and feasibility for use in a gas tank. After identifying the potential materials, the mechanical properties of each potential material, as well as, the diffusion of gasoline through the material was examined. Diffusion and material strength are very important properties. These relate directly to the determination of the gas tank wall thickness that would be needed to have near-zero gas emissions and a gas tank strong enough to meet the safety regulations. This evaluation of the materials is discussed in the Diffusion section and in the Mechanical Properties section. Once the diffusion and strength properties were determined, wall thickness can be determined for each applicable material and combinations may be produced if necessary.

The third stage was to identify processes that are capable of producing large numbers of gas tanks. After possible processes were found, they were matched with compatible materials. A total capital investment and return on investment was determined for each situation. After this, the most profitable process and material pair was chosen.

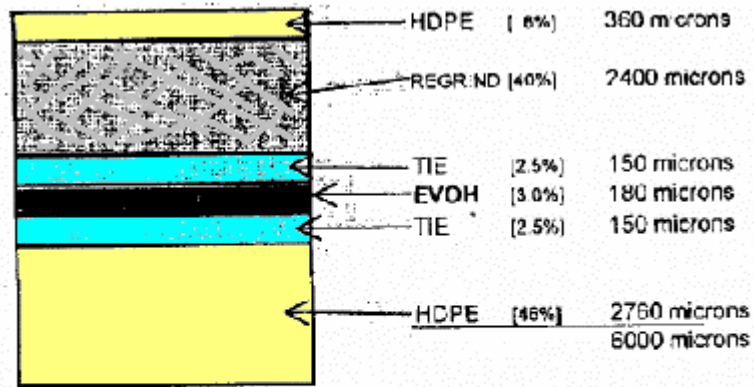
The fourth design stage details the tank processing. The process used to produce the structural layer is outlined in detail. The processing of the barrier layer is discussed as well as the final assembly of the gas tank.

The final stage involves the evaluation of the risk and uncertainty associated with the process. This stage also includes the strategy that will be used to implement the creation of a business that would produce the designed gas tanks.

Current Gas Tanks

Until the 1980s fuel tanks in automobiles were constructed of steel. During the late 1980s and especially in the 1990s and 2000s, the gasoline tank industry began to produce tanks made from high density polyethylene (HDPE). The plastic tanks were lighter, cheaper, less susceptible to vibration, and capable of meeting safety and emissions standards. The steel used to produce gas tanks is 20 gage low carbon steel. The steel is usually hot dipped in a mixture of tin and zinc. The tin-zinc hot dip increases the tank's ability to resist corrosion. It is estimated that more than 70% of all gas tanks produced in North America are constructed of plastic.¹ All plastic gas tanks currently in use are high density polyethylene. One major gas tank producer, Visteon, uses a blow molding process to produce a six layer tank with alternating layers of ethylene vinyl alcohol (EVOH) and high density polyethylene. The tank is a six-layer design constructed of high density polyethylene, linear low density polyethylene, ethylene vinyl alcohol, and a regrind layer of high density polyethylene waste. The cross section of the tank wall is found below.

¹ See Book References. #10. Alvarado, Peter J. "Steel v. Plastic: The Competition for Light Vehicle Fuel Tanks" **The Member Journal of The Minerals, Metals, and Materials Society**, vol. 48, 1996. pp. 22-25.



Volume: 60 Liters
 Weight: 8 Kg

FIGURE 1: Cross section of Visteon gas tank.

Visteon sells directly to automobile manufacturers. Therefore, the price for which their gas tanks are sold is not readily available. In order to estimate the price of the Visteon gas tank, their process was modeled. By knowing the materials used, as well as the process, and using equipment estimates obtained, the price of a Visteon tank was estimated. The price was found to be \$53.00 per tank, based on an assumed return on investment of 15%. While the exact return on investment sought by Visteon is unknown, 15% is taken as a typical desired return. Visteon also uses this technology to produce many of the parts that make up their fuel storage and delivery system.

The steel and plastic tanks that are presently produced have been proven to be safe for use in consumer automobiles. The cross-linked polyethylene tanks are not recyclable while steel tanks are recyclable. The steel tanks are also capable of achieving near zero emissions whereas the polyethylene tanks cannot,² even with multiple layer technology.

There is no standard gas tank design that car manufacturers simply insert into cars. Every company and many makes have their own unique gas tank design. A quick survey of a gas tank catalogue will show that gas tanks will vary significantly from manufacturer to manufacturer. They will vary in size, markings, hole locations,

² See Book References. #10. Alvarado, Peter J. "Steel v. Plastic: The Competition for Light Vehicle Fuel Tanks" The Member Journal of The Minerals, Metals, and Materials Society, vol. 48, 1996. pp. 22-25.

dimensions, and capacity. The figures below give an example of the various gas tanks used in the automobile industry.

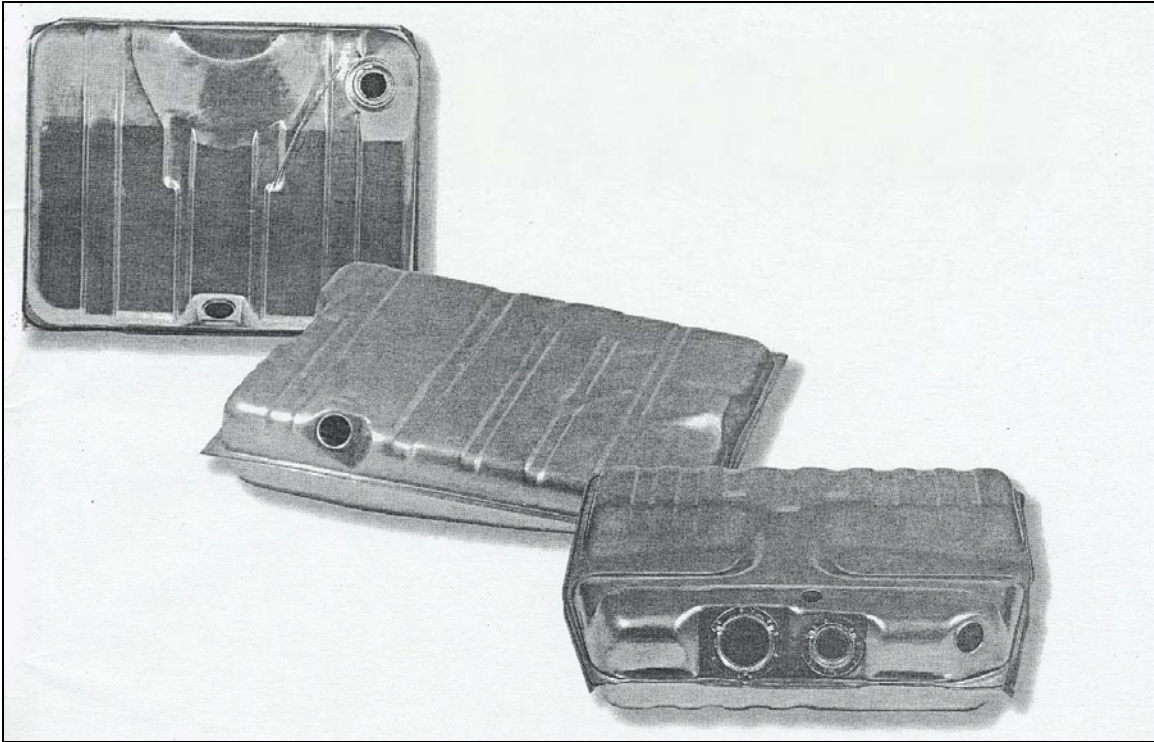


FIGURE 2: Some typical Chrysler gas tanks.³

The figure above shows three typical gas tanks from the Chrysler Company. These gas tanks are simpler, box-like designs, with the exception of the slant in the middle gas tank. It is noticeable that the holes in each gas tank are in different positions from the other gas tanks: on top, on the edge, on the side.

³ Chrysler Gas Tanks. Pg. 35. 1998 Gas Tank Catalogue. American Designers.

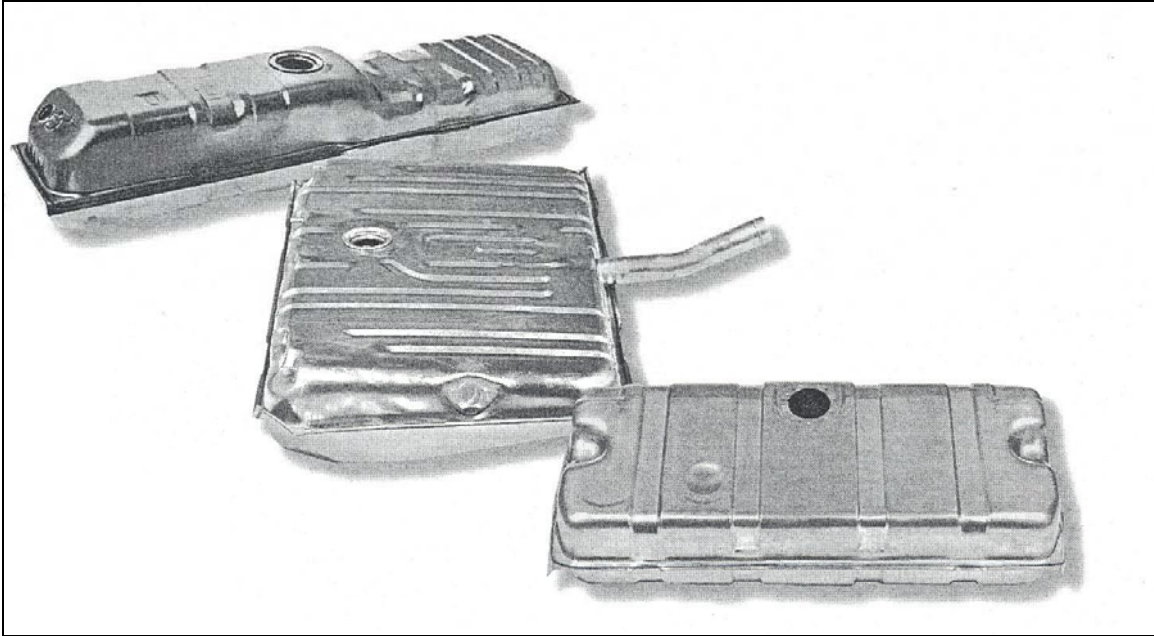


FIGURE 3: Some typical GM gas tanks.⁴

The figure above shows three typical gas tanks from General Motors (GM). The simple design for the bottom gas tank is easily noticeable. However, the top gas tank is much longer than the typical gas tank, and is abnormally tall.

Some GM gas tanks also have filler necks as part of the gas tank. A filler neck is used for fuel injection purposes.

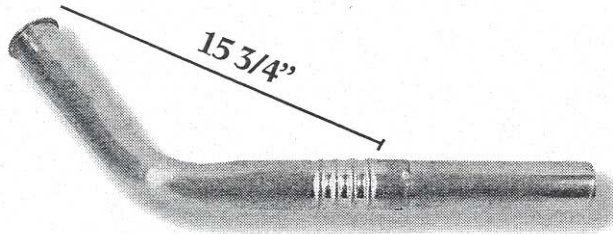


FIGURE 4: Sample filler neck.⁵

The above figure illustrates a filler neck for a 2000 Honda Accord. Generally these are sold separately from the gas tank, but some GM gas tanks and filler necks are sold as one part. Ultimately, this varies from manufacturer to manufacturer. For plastic gas tanks however, filler necks can present a problem. Gasoline tanks cannot be produced that feature an attached filler neck. The filler neck would need to be produced

⁴ GM Gas Tanks. Page 51. 1998 Gas Tank Catalogue. American Designers.

⁵ Sample Filler Neck. Page 191. 1998 Gas Tank Catalogue. American Designers.

separately and added later. Separate filler necks would not be included. The process developed here focuses only on the production of gas tanks. However, the gas tanks can be designed to accommodate a filler neck if needed.

Safety and Emissions

In order for the tanks to be marketable, they must meet all current safety and emissions qualifications. These requirements are listed and discussed below.

Safety Regulations

Safety regulations were established in the Federal Motor Vehicle Safety Regulations Handbook item number 571.301 Standard No. 301: Fuel Systems Integrity specifies the requirements, testing procedures, and safety requirements for the integrity of gasoline tanks.⁶ This document applies to passenger cars with a gross vehicle weight rating (GVWR) of 4536 kg or less. GVWR is a value specified by the vehicle manufacturer as the loaded weight of a single vehicle. The vehicle is considered to be loaded after life-like test dummies have been added.

Fuel Spillage

The purpose of this test is to reduce deaths and injuries occurring from fires that result from fuel spillage during and after motor vehicle accidents. Fuel spillage is measured after a barrier crash. Fuel spillage cannot exceed 28 g from impact until motion of the vehicle has ceased and cannot exceed 142 g in a 5 minute period following cessation of motion. After 5 minutes it should not exceed 28 g in any one minute period until an additional 25 minutes have passed. In rollover tests, the fuel spillage cannot exceed 142 g for first 5 minutes at each 90° angle. After the 5 minutes at each 90° angle the spillage in a one minute period cannot exceed 28g.

⁶ Federal Motor Vehicle Safety Standards and Regulations. U.S. Department of Transportation. <http://www.nhtsa.dot.gov/cars/rules/import/FMVSS/crashes>.

Crash Tests

- Frontal Barrier Crash- The test vehicle must be moving up to 48 km/hr (30 mph) and crash into a barrier perpendicular to the line of motion or up to 30° in either direction of the line of travel. Test procedures outline detailed methods for preparing the vehicle. Fuel spillage will not exceed limits specified in the Fuel Spillage section above.
- Rear Moving Barrier Crash- The test vehicle must be moving up to 48 km/hr (30 mph). Fuel Spillage limits still apply.
- Lateral Moving Barrier Crash- The vehicle is impacted laterally on either side by a barrier moving up to 32 km/hr (20 mph). Fuel spillage limits apply.
- Static Rollover- The vehicle is rotated on its longitudinal axis to each successive increment of 90° following frontal, rear and lateral impacts. Fuel spillage limits apply.

General Test Conditions

The fuel tank needs to be filled to any level between 90% and 95% of capacity with Stoddard solvent, having the physical and chemical properties of a type 1 solvent, according to Table I ASTM Standard D 484-71. The fuel system also needs to be filled. These conditions apply to all crash tests.

If the vehicle uses an electric pump, it must be running during all tests. The parking brake must be disengaged and the transmission in neutral for all tests. The vehicle should be loaded as prescribed in the Federal Motor Vehicle Safety Regulations handbook.

EPA Emissions Regulations

There are two regulations that gas tanks must comply with during testing. These evaporative emission standards must be met for a tank to be suitable for use in consumer automobiles. First, a vehicle must emit no more than a total of 2.0 g of hydrocarbon (or, in the case of methanol-fueled vehicles, hydrocarbon and methanol), measured during the diurnal (24 hour) cycle. Second, the vehicle must meet a running loss test standard of 0.05

g/mi (0.03 g/km). These standards apply to light-duty vehicles⁷. Light-duty trucks must meet the same standards, except that light-duty trucks of gross vehicle weight rating (GVWR) between 6,000 and 8,500 pounds (2,700 to 3,900 kg) which have nominal fuel tank sizes of 30 gallons (110 liters) or more are subject to a relaxed diurnal/hot soak standard of 2.5 grams. The hot soak test is a one hour test which is conducted right after the engine is turned off. Hot soak tests are carried out at 95⁰ F. This temperature is achieved by either placing a heater under the gasoline tank or running the engine until the gasoline tank reaches 95⁰ F. All of these tests are conducted in sealed housing for evaporative determination (SHED).⁸ In the near future, California is planning to adopt a zero emissions standard⁹. The new zero emission standard states that no more than 0.35 g of hydrocarbon may be emitted during a 24 hour period. The EPA and Federal Motor Vehicles Department have detailed testing procedures which explain how to perform the tests and how to report the results. These testing procedures are universal for every automobile manufacturer that sells cars in the United States.

Materials

Several materials were identified as suitable for the construction of gasoline tanks. The materials chosen were identified based on their properties. They were also chosen based on their feasibility for use in an actual gasoline tank. The materials identified and examined were:

- Epoxy Resins
- Polyethylene
- Curv®
- Glass-Filled Nylon
- Kynar Resin
- Polyurethane

⁷ EPA Emissions Specs

⁸ Emission Lab Tour. http://www.ott.doe.gov/otu/field_ops/emis_tour/evap.html

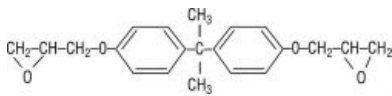
⁹ See Book References. #10. Alvarado, Peter J. "Steel v. Plastic: The Competition for Light Vehicle Fuel Tanks" The Member Journal of The Minerals, Metals, and Materials Society, vol. 48, 1996. pp. 22-25.

- Ethylene Vinyl Alcohol
- Maleic Anhydride

These materials and their potential application for use in a polymer gas tank are discussed below.

Epoxy Resins

Epoxy resins are engineered polymers that have a broad range of use, but are often times used for adhesive purposes and/or structural reinforcement. There are millions of epoxies available today but the most common have a DGEBA (diglycidyl ether of bisphenol-A) base and use an aliphatic amine as a curing agent.



It can be seen from the structure that the functional groups are on the ends of the molecule. These are extremely reactive since the bond angles do not match the geometry of the carbon angle, thus causing instability in the bonds. Oxygen is fairly electronegative which causes a static moment in the molecule. Heat and UV light can cause the epoxide groups on the end to break open, thus starting the chain reaction.

Because of the phenol groups, very large molecular weights can be attained in epoxide matrices. The benzene ring is also very stable which means that epoxides exhibit a natural chemical resistance. Solvents can destroy the structural integrity of an epoxide but additives can be used to lessen this effect.

Curing agents, in the simplest terms, finalize the reaction. Different curing agents can enhance or decrease epoxy characteristics such as chemical resistance, tension strength, thermal resistance, etc. The cure can sometimes take place at room temperature or might require an autoclave for elevated temperatures and pressures.

For our purposes an epoxy with certain properties would be needed. It must be dense enough to prevent diffusion of gasoline through tank walls, be strong enough to withstand an impact, withstand high temperatures for extended periods of time (hrs) and have long term physical and chemical resistance.

Epoxies with these characteristics are available. Aromatic primary amines and acid anhydrides provide improved performance over the basic aliphatic amines but are expensive to use because of the elevated temperatures/pressures and their complexity when reacting. Autoclaves and heaters would require large equipment costs, as well as large amounts of utilities.

Data¹⁰ on diffusion of toluene through DGEBA (cured with NMA) shows that epoxides are good diffusion barriers. Octane, however, is a longer chain which would not diffuse as easily so the comparison is accurate.

Epoxy physical properties exceed those of HDPE in almost every category. This is due to the high molecular weight and steric forces exhibited by the phenol groups. Our process needs to be quick and efficient to keep with the demand of production. Epoxies would be difficult to use due to high viscosities. Another drawback of using epoxies is long cycle times. The curing process is slow, causing the cycle times to be long.

The following is a table summarizing some of the important material properties that will be taken into account when considering the material.

Properties¹¹	
Glass Transition	150 °C
Softening/ Processing Point	NA / 160 °C
Permeability/ Diffusivity ¹²	NA / 5.8e-11 cm ² /s
Charpy Impact	NA
Price (\$/lb)	\$1.40

TABLE 1: Epoxy properties.

Polyurethane

Polyurethane is a common polymer made by the reaction between polyol and isocyanate liquids. It is extremely versatile and is used in many everyday applications. Polyurethane has qualities comparable to polyethylene, but is typically more brittle than either polypropylene or polyethylene. Additives can be used to alter the chemical

¹⁰ See Book References. #4. Caruthers, James. Handbook of Diffusion and Thermal Properties of Polymers and Polymer Solutions. New York, AIChE, DIPPR, 1998.

¹¹ Taken from <http://www.matweb.com>

¹² See Book References. #4. Handbook of Diffusion and Thermal Properties of Polymers and Polymer Solutions- AIChE, 1998

properties of the polymer. The polyol chain size can also be adjusted to alter the chemical properties.

The following is a table summarizing some of the important material properties that will be taken into account when considering the material.

Properties¹³	
Glass Transition	N/A
Softening/ Processing Point	94-245°C/ 100°C
Permeability/ Diffusivity ¹⁴	NA / 1.5e-7 cm ² /s
Charpy Impact	0.9
Price(\$/lb)	N/A

TABLE 2: Polyurethane properties.

Polyethylene

Polyethylene is probably the most common plastic encountered in daily life and the most popular plastic in the world. Because it is a polymer, it consists of a long chain of carbon atoms with two hydrogen atoms attached to each carbon atom.

Polyethylene is available in a variety of forms: low density (LDPE), linear low density (LLDPE), medium density (MDPE), high density (HDPE), and cross-linked (XLPE). Cross-linked polyethylene is formed by keeping the product at an elevated temperature for an extended period of time allowing the polymers to cross link. During cross-linking, the polymer chains join to form one large molecule. Cross-linked polyethylene is the strongest form, but it is not recyclable.¹⁵

Polyethylene has various advantages over metal.¹⁶ First, it is inexpensive. The current price for high density polyethylene is about \$0.53/lb. For example, polyethylene is corrosion and chemical resistant. Polyethylene molded objects will not corrode and can be designed to accommodate many weather changes and environments. Polyethylene is also impervious to many chemical compounds, lowering the amount of impurities that

¹³ Taken from <http://www.matweb.com>

¹⁴ See Book References. #4. Handbook of Diffusion and Thermal Properties of Polymers and Polymer Solutions- AIChE, 1998

¹⁵ Centro Incorporated. <http://www.centroinc.com/molding.htm>

¹⁶ Solar Plastics, Inc. <http://www.solarplastics.com>.

build up on metal tanks. Although polyethylene is not as strong as metal, it is strong enough for our application. The simple structure and its versatility make it the simplest of all the commercial polymers. It can be designed to be impact and dent resistant, especially if the thickness is increased and if it is of the cross-linked form. Polyethylene can be easily designed into various shapes, which allows polyethylene gas tanks to be made to fit into many empty spaces. This is not possible with metal. It is lighter for better fuel economy and cheaper as a raw material. Also, the polyethylene can be dyed an array of colors, so that no painting would be necessary.

There are two main disadvantages to using polyethylene. Though it is strong enough for all kinds of applications and products, it is still not as strong as metal for comparative thicknesses. So the strength of the polyethylene product in a particular application will always be a decisive factor to take seriously. The second is that the fuel in the gas tank will diffuse through polyethylene more readily than metal. So a coating could be added to the polyethylene gas tank in order to reduce or eliminate any emissions. If these two problems can be overcome, polyethylene is a good material for gas tank production. We would choose high density polyethylene over the other lower density types because the high density reduces diffusion through the material. It would also have to be cross-linked for added strength.

Linear Low Density Polyethylene

Linear low density polyethylene (LLDPE) is used as an adhesive layer between polymer layers. The LLDPE is required for proper adhesion between ethylene vinyl alcohol (EVOH) and other polymers¹⁷. Since EVOH is a potential barrier layer material, LLDPE may be needed as a component of the gas tank. LLDPE provides very little strength to the overall structure of the tank, and does little to prevent diffusion since it is a low density polymer. LLDPE is very inexpensive costing \$0.46/lb. It is purchased in pellet form. The Vicat softening temperature of LLDPE is 92.8°C and the melting temperature is 130°C¹⁸. A major consideration when using LLDPE is that it does not

¹⁷ See Book References. #12. Ellis, Thomas S. "Structural and Material Features That Influence Emissions From Thermoplastic Multilayer Fuel Tanks", *SAE Technical Paper Series*, 2003.

¹⁸ See MatWeb link: <http://www.matweb.com/search/SpecificMaterial.asp?bassnum=O3850>

adhere to all materials. Thus, if a barrier layer of EVOH is used, an adhesive layer is required for the EVOH to adhere properly, but care must be taken to insure that the LLDPE will adhere to the other polymer material.

Curv®

Curv® is a polypropylene product made by BP. Curv® is a multi-layer material with alternating layers of honeycomb structures of polypropylene and sheets of polypropylene. This arrangement dramatically increases the mechanical and physical properties of Curv®. The ultimate tensile strength of Curv® is 180 MPa and the Charpy Impact strength is 12 J/cm². The impact strength of Curv® is higher for lower temperatures; this type of behavior is opposite the behavior seen in most plastics, composites, and metals. Low temperatures are a concern when using plastics for fuel tanks, but this property of Curv® gives it an advantage over other composite materials. Curv® is lightweight and is easily processed by thermoform stamping. Thermoform stamping Curv® does not significantly hinder its' mechanical properties. Curv®'s fibers are able to be partially extended allowing for more even fiber distribution and minimal thinning in the highly drawn areas compared to other reinforced composites. Since Curv® is 100% polypropylene it is fully recyclable and thus has a definite advantage over high density polyethylene (HDPE) and other reinforced composite materials. HDPE is cross-linked when it is used for tanks in order to make it stronger, and thus cannot be recycled. Glass and fiber filled materials are only partially recyclable. The following list summarizes Curv® properties:

- Does not dissolve or swell in the presence of gasoline
- High impact strength
- 100% recyclable
- Lightweight due to its low density
- Comes in preformed sheets of specified thickness from 0.3 mm – 3.0 mm (eliminates the need for expensive equipment needed to produce polymer sheets)
- Maintains good mechanical properties after being deformed/re-shaped
- Low density results in higher diffusion rates than other materials

- Costs \$4.46/m²area/mm thickness

Curv®'s properties and characteristics give it a definite advantage for use as a structural material over other composite materials.

Glass-Filled Nylon

Glass-filled nylon composites have improved mechanical properties compared to their straight nylon bases. Nylon 6, Nylon 6/6, and Nylon 12 with 10%, 20%, and 30% E-glass random filling were considered for this project. The tensile strengths and yield strengths of the glass-filled nylon composites were nearly double the tensile and yield strengths of the straight nylon materials. However, the impact strengths, which are more important properties for gasoline tanks, were lower for the glass-filled nylon composites than for their straight nylon counterparts. Even though the stiffness and resistance to wear are much greater for the glass-filled nylons, they are more brittle and less resistant to cracking when impacted.

KYNAR® Resin

KYNAR® 1000 HD resin is a polyvinylidene fluoride homopolymer made by Atofina Chemical Corporation. Kynar resin has a Charpy Impact strength of only 2.2 J/cm² and a yield tensile strength 50 MPa. Because of poor mechanical properties, Kynar resin is not a good structural material, but due to its diffusive properties it is being considered for use as a barrier layer. Using Kynar as a barrier will reduce the diffusion of gasoline through the tank wall and protect the tank material from interaction with the gasoline. Kynar has an advantage over other materials for use as a barrier because it is highly resistant to hydrocarbons, is somewhat flexible, and has a low diffusivity. KYNAR® 1000 HD costs \$10.51/lb and comes in 55 lb. bags. The high cost of this material is the major concern for its use as an inner coating for gasoline tanks.

Ethylene Vinyl Alcohol

“EVAL Resins are characterized by their excellent processability and outstanding barrier properties. The key to this remarkable balance is the combination of the proper co-polymerisation ratio of ethylene to vinyl alcohol, the carefully selected degree of

polymerization, and the unique proprietary manufacturing process used in the production of EVAL copolymers.”¹⁹

Ethylene vinyl alcohol (EVOH) is the barrier of choice in industry when the purpose is to keep gases in or out. EVOH has a Vicat softening point of 173°C (343°F) and a melting point of 181°C (358°F)²⁰. Thus, EVOH would be suitable for use in a gasoline tank under normal operating conditions. The glass transition temperature is 69°C (153°F).

The following is a summary of the important properties of EVOH.

Properties ²¹	
Glass Transition	69 C
Softening/ Processing Point	173 C/ 220 C
Permeability/ Diffusivity	0.0007 g-mm/ 100in ² - 24hr- 1 atm/ N/A
Charpy Impact	N/A
Price(\$/lb)	\$2.65

TABLE 3: Properties of EVOH.

Maleic Anhydride

Maleic anhydride is used for various applications, such as in the production of unsaturated polyester resins, alkyd resins, agricultural chemicals, malic acid, copolymers, fumaric acid, lubricant additives, surfactants, and plasticizers. It is also used as an adhesive. All of these applications are possible because maleic anhydride is a highly reactive and versatile raw material.²²

The structure of maleic anhydride is shown in the figure below:

¹⁹ EVALCA. Barrier Properties. http://www.evalca.com/otr_calc.html

²⁰ See MatWeb link: <http://www.matweb.com/search/SpecificMaterial.asp?bassnum=PEVAL3>

²¹ See MatWeb link: <http://www.matweb.com/search/SpecificMaterial.asp?bassnum=O1890>

²² Maleic Anhydride Applications. Barket. http://www.bartek.ca/maleic_app.html

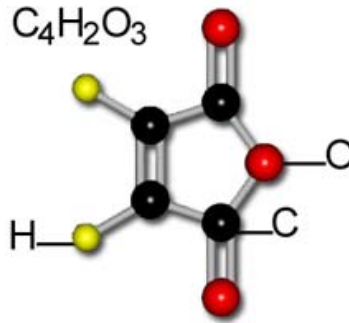


FIGURE 5: Molecular structure of maleic anhydride.

Maleic anhydride can be used in a gas tank as an adhesive. It can bind ethylene vinyl alcohol to a layer of polymer. A thin layer of maleic anhydride can be extruded if it needs to be coated on another material. BP, for example, can create a Curv® product that has a thin layer of maleic anhydride.

Gas Tank Design

Diffusion

Diffusion is the term for mass transfer through a medium. This occurs naturally in nature and is usually driven by static pressure and concentration gradients. Diffusion explains why filters and membranes work. Diffusion can also take place through dense solids such as polymers. For this reason this topic is being applied to the gas tank.

Future “zero” emissions requirements of 0.35g/ day set an upper limit on what can diffuse through the gas tank. The tank itself is a polymer composite that will most likely have multiple layers. This section will concentrate on creating the model for the barrier layer of the gas tank.

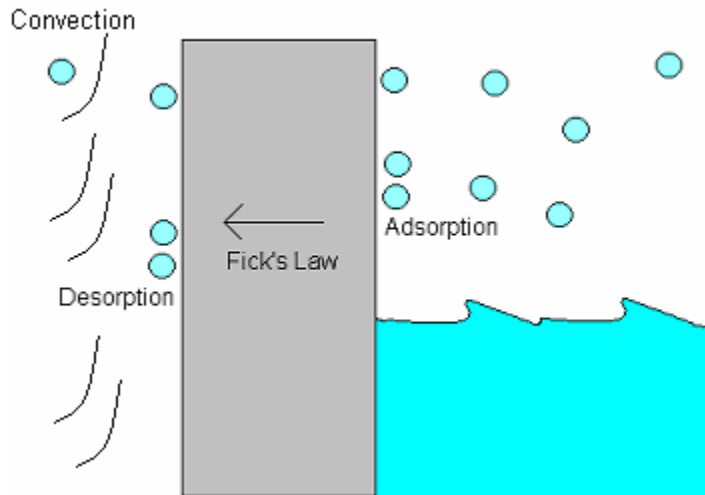


FIGURE 6: Diffusion model.

The diffusion model for the tank can be broken down into four sections. First there is adsorption of the molecule to the inner surface of the barrier. Second, there is diffusion through the barrier which can be described by Fick's Law of diffusion. Third, there is desorption of the molecule into the atmosphere from the outer barrier. And finally because it is exposed to the elements there is a possibility of a convective mass transfer resistance²³. These sections will be discussed in detail below. One important detail that is in effect throughout this explanation is that the model is assumed to have already reached steady state. This is a reasonable assumption because the tank takes weeks to reach steady state, not years²⁴.

²³ Transport Properties of Gases in Polymers- Experimental Methods

²⁴ Technical Bulletin No. 180 Chemical and Solvent Barrier Properties of EVAL Resins

Adsorption- Henry's Law



FIGURE 7: The adsorption process.

Henry's Law states that the concentration absorbed into the barrier, C , is proportional to the vapor pressure of the gaseous solvent, p , and Henry's solubility coefficient, S :

$$C = S \times p$$

Diffusion- Fick's Law



FIGURE 8: Diffusion through the barrier.

Once the molecule has been adsorbed into the polymer surface it will then diffuse through the barrier layer. Its behavior can be described by Fick's Law of diffusion²⁵ which is:

$$N_{az} = D_{ab} \times \frac{dc_a}{dz}$$

where N_{az} is the flux out, D_{ab} is the diffusion coefficient, c_a is the concentration of the diffusing species, and z is the thickness of the barrier. The law in its present form is for diffusion in one dimension. Following diffusion through the barrier, the molecule will then be desorbed naturally into the atmosphere.

Convective Mass Transfer

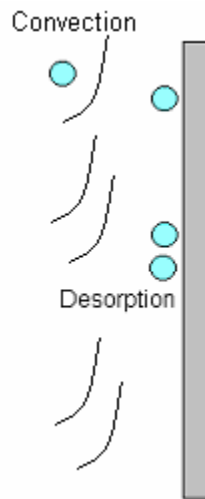


FIGURE 9: Convection and desorption on the exterior of the tank, past the barrier.

The final resistance which may be present on the exterior is the effect of convective mass transfer. To evaluate this effect, the convective mass transfer coefficient needs to be evaluated by using a correlation involving the Schmidt number, which is the

²⁵ See Book References. #6. Welty, Wicks, Wilson, and Rorrer. Momentum, Heat and Mass Transfer, 4th Edition. New York, Wiley, 1999.

mass transfer analogy to the Nusselt number and the Grashof number. This correlation²⁶ is

$$k_c = \frac{D_{ab}}{x} \times (0.332 \times Gr_x^{0.5} \times Sc^{1/3})$$

where k_c is the convective mass transfer coefficient, D_{ab} is the diffusion coefficient, x is the local length (tank length), Gr_x is the Grashof number, and Sc is the Schmidt number. Once the convective mass transfer coefficient has been found, a mass balance can be used to determine the concentration at the outside of the wall. This concentration is important because it is used as the reference to determine if the convective mass transfer is negligible. This concentration is compared to the desorption concentration on the outer barrier layer. If the outer layer barrier layer concentration is larger than the concentration found by the convective mass balance equation then convective mass transfer is not negligible but if the concentration at the barrier is less than it can be ignored. An important aspect of this comparison is that the convective mass transfer coefficient itself cannot be used to determine if convection is negligible since the flux out of the boundary layer is dependent on the concentration of material present. The equation to evaluate the concentration on the outside is:

$$k_c * A_x * (C_{a_s} - C_{a_\infty}) = W_a$$

where k_c is the convective mass transfer coefficient, A_x is the surface area of the tank, C_{a_s} is the surface concentration and C_{a_∞} is the concentration in the sink. Convective mass transfer is an important phenomenon but in the evaluation of this gas tank the worst case scenario must be taken into account to model the best gas tank. Therefore, the added

²⁶ See Book References. #6. Welty, Wicks, Wilson, and Rorrer. Momentum, Heat and Mass Transfer, 4th

resistance of the outer boundary layer should not be included. Another important factor in making this decision is the availability of solubility coefficients.

EVALCA was contacted for information on solubility coefficients. EVALCA informed our group that their EVAL barrier is tested with Ref Fuel C, a 45% Toluene, 45% iso-octane, 10% Ethanol mixture. Each solvent's solubility is rated as soluble, partially soluble, or insoluble. Toluene and iso-octane are rated as insoluble in their F-Series EVAL barrier while ethanol is only partially soluble²⁷. Ethanol is partially soluble because of the OH functional group. Ethanol contact can be prevented by another layer such as HDPE between the EVOH and ethanol. However, this allows the toluene and iso-octane to reach the EVOH barrier. By definition, if the substance is insoluble then the permeability is zero because the expression $P = S \times D_{ab}$ would have a zero for S. But however small the solubility of the solvent is in the EVOH it still must have some solubility because there is a loss of material when the gas tanks are tested. This small change makes measuring the solubility very difficult. Thus, to solve this problem, companies such as EVAL use permeability to take both effects into account. The idea that a substance can have a low solubility but higher diffusivity seems rather odd but it can happen²⁸. Examples of this can be seen when membranes are used to separate gases, some gases simply diffuse faster than others even though both are soluble in the membrane. For these reasons our group is using the overall permeabilities, much like overall heat transfer coefficients, in order to find the worst case scenario mass flux out of the gas tanks.

Edition. New York, Wiley, 1999.

²⁷ Technical Bulletin No. 180 Chemical and Solvent Barrier Properties of EVAL Resins

Diffusion Model

After having evaluated the four sections of the boundary layer, a mathematical model can be created to describe the diffusion through the barrier. Permeability is the product of Henry's solubility coefficient and the diffusion coefficient²⁹.

$$P = S \times D_{ab}$$

By integrating Fick's Law for one dimensional diffusion, the differential equation becomes,

$$J = \frac{D_{ab}(C_2 - C_1)}{L}$$

where C_2 is the external concentration at the barrier boundary and C_1 is the internal concentration at the barrier boundary. Substituting Henry's Law into the integrated Fick's Equation yields:

$$J = \frac{D_{ab} \times S (p_2 - p_1)}{L}$$

And finally substituting the definition of permeability into the equation above yields the final version of Fick's Law that will be used to determine the thickness needed to meet EPA regulations.

$$J = \frac{P \times A \times (p_2 - p_1)}{l}$$

J is the flux out, P is the permeability, A is the surface area of the tank, p_2 is the external partial pressure of the gas, p_1 is the internal partial pressure of the gas, and l is the thickness of the boundary layer. This equation will describe the flux out of the tank. The

²⁸ Structural and Material Features that Influence Emissions from Thermoplastic Multilayer Fuel Tanks- SAE Technical Paper, Thomas S. Ellis.

²⁹ Transport Properties of Gases in Polymers- Experimental Methods- Oil & Gas Science and Technology- Rev. IFP, Vol 56 (2001), No 3, pp. 245-259

EPA emissions limit, P, A and the partial pressures are known. The only unknown is the thickness.

Thickness Determination Based on Diffusion

If the partial pressures of the solution for the given situation, the surface area, and the time frame is known then a transmission rate can be established. These rates are established from SHED, Sealed Housing for Evaporative Determination, tests.

The units are grams- mm/ area- time- pressure where as permeability is in mol/ m-s-Pa. Dimensional analysis shows that by changing moles to grams and length to area, the transmission rate is obtained. The following equation is the same flux equation derived above but using the transmission rate expression.

$$Thickness = \frac{Permeation \times Area}{Diffusion}$$

Applying this new expression for the top performing materials, the thicknesses required to meet EPA regulations are given in the table below³⁰.

Material	Thickness Required(mm)
Nylon	0.566
HDPE	7825
Curv	8607
Kynar	0.132
EVOH	0.033

TABLE 4: Comparison of thickness needed to meet diffusion standards set by the EPA.

³⁰ Technical Bulletin No. 180 Chemical and Solvent Barrier Properties of EVAL Resins- www.evalca.com

Using these numbers, a comparison will be made between the structural numbers to determine how many layers will be needed. This comparison will also determine the function of the material, whether it is for diffusion and structural, just diffusion or just structural.

Mechanical Properties

The following is a list of the most important mechanical properties of a material to investigate when trying to evaluate a material's strength:

- tensile strength
- yield strength
- toughness
- tensile impact strength
- Izod impact strength
- Charpy Impact strength
- flexural strength
- Rockwell hardness
- high speed puncture strength

The tensile strength is the maximum stress a material can withstand during a tensile test. The yield strength is the maximum stress a material can undergo without going into plastic deformation (beyond this strength the material cannot return to its original shape). Tensile and yield strengths are determined by stretching a sample in the longitudinal direction at a fixed rate (moderately slow) until the sample breaks. Using the data taken during these tests a stress versus strain curve can be constructed for a material. A sample of a stress strain curve is shown below in FIGURE 10. The toughness of a material is the area under the strength versus strain curve (black diagonal lines in FIGURE 10). This property describes a material's resistance to breaking or fracturing. Toughness is linearly related to thickness. However, it is hard

to obtain stress versus strain curve for most materials, so this makes it difficult to use toughness for determining the material thickness needed.

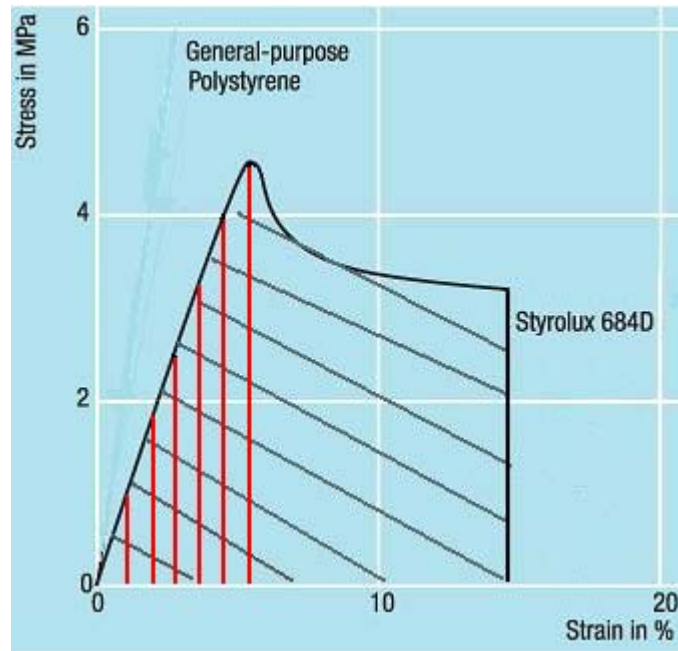


FIGURE 10: Toughness of Styrolux (polystyrene product).³¹

The tensile impact strength of a material is the energy required to fracture a specimen under a shock tensile loading. The sample is placed under tension and then impacted. This test is usually done for thin polymers or polymers too flexible for Izod or Charpy impact tests. The Izod impact test represents the energy per thickness needed to fracture a specimen held at one point. The Izod impact energy is not the best property to used, because the test sample is only held at one point, thus it does not provide the most accurate simulation of the situation in which the tank would be impacted during a collision. The Charpy impact energy (J/cm^2) is the energy per cross sectional area (width x thickness) absorbed by a material before it breaks or fractures. The Charpy Impact energy of a material is similar to a material's toughness. Also, the Charpy impact energies for various materials are more readily available. The Charpy Impact Energy is the area under the stress versus strain curve up to the point of maximum stress (red vertical lines in FIGURE 10).

³¹ BASF.

<https://www.plasticsportal.net/wa/EU/Catalog/ePlastics/doc/BASF/prodline/styrolux/properties.xdoc#N1000F>

This test is performed by impacting a specimen held at two points (FIGURE 11). The energy lost by the swinging pendulum is divided by the thickness and width to get the Charpy impact energy of the material. This situation fits most closely to the situation in which a tank will be impacted during a collision.

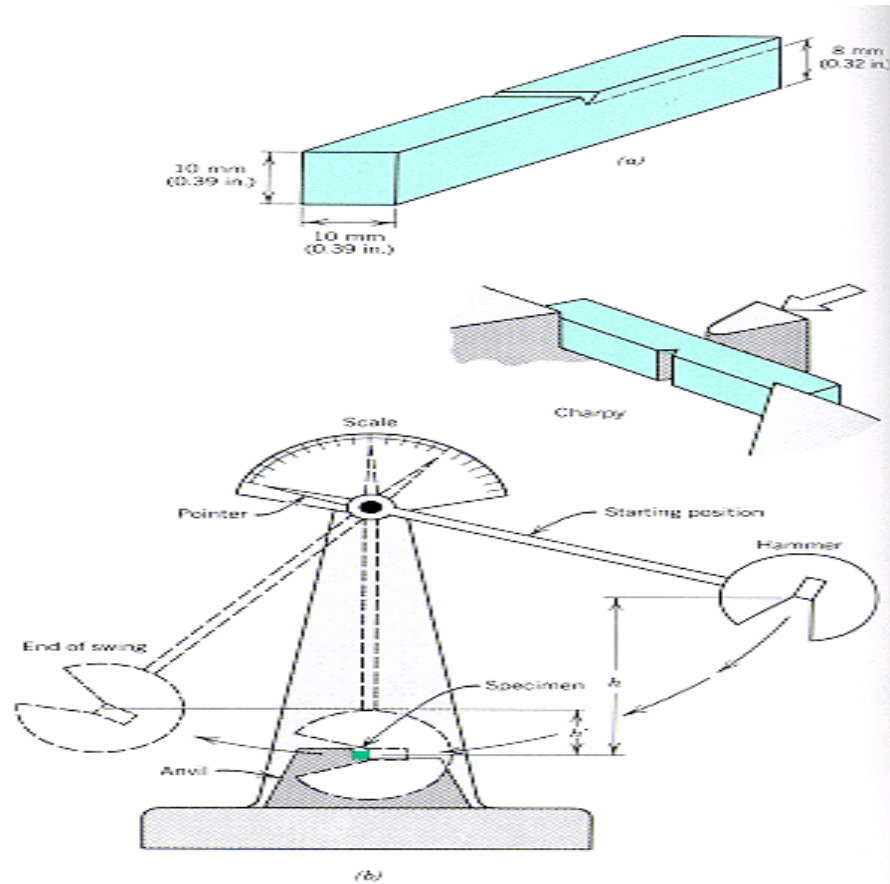


FIGURE 11: Charpy Impact test setup.³²

Since Charpy impact energy is related to toughness, it would be reasonable to presume that it is also linearly related to thickness. The Charpy impact energy of a sample represents the total energy required to break a sample divided by the cross sectional area impacted. This energy is the energy lost by the swinging pendulum after striking the sample divided by the product of the width and thickness area of the sample impacted. FIGURE 12 below shows a schematic of the sample area that is impacted by the pendulum head.

³² Charpy Impact. <http://www2.latech.edu/~jordan/courses/me215/ManualF03/04CharpyImpact.htm>

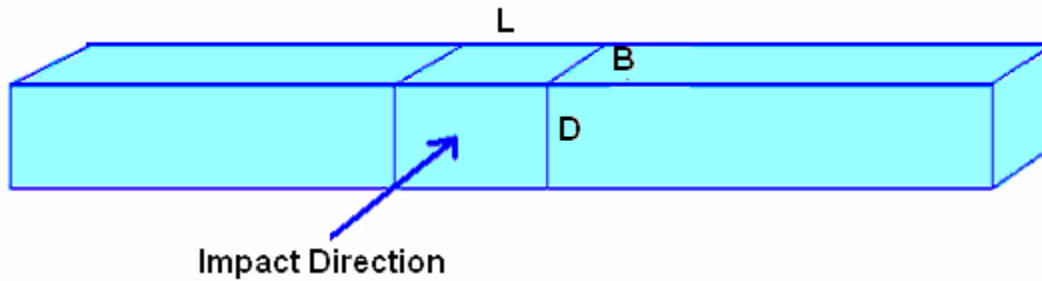


FIGURE 12: Schematic showing impact dimensions for Charpy Impact tests.

The width of the sample (D) and the thickness of the sample (B) are the dimensions used to calculate the cross-sectional area of the sample. The length of the sample (L) is not important in determining the cross-sectional area of a sample. The important dimension is the cracked cross section. Since the Charpy impact energy for a given sample is dependent upon the width and thickness of the impacted area, some relationship should be present. Research has determined that the Charpy impact energy of a material is directly related to thickness. FIGURE 13 below shows the direct relationship between total impact energy needed to break the sample and thickness. If the width is held constant, the total impact energy needed to break the sample will increase linearly with the thickness. Charpy impact energies are available for many materials, so combining this with its relation to thickness makes it the optimum property to use for comparing our materials to the steel used in current tanks.

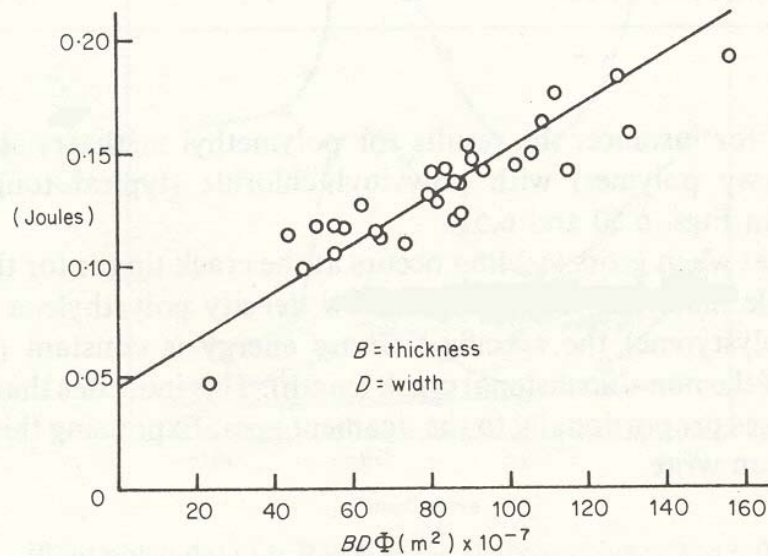


Fig. 6.49. Typical results for cast PMMA sheets obtained on Charpy tests. (After Plati and Williams.⁵³)

FIGURE 13: Charpy impact test results for polymethyl acrylate (PMMA).³³

In FIGURE 13 above, B is the specimen thickness, D is the specimen height, and Φ is a calibration factor. The calibration factor Φ is used to determine the specific fracture energy. The specific fracture energy is the actual energy needed to fracture a sample if the sample did not contain a notch. Due to the presence of the notch, the specific fracture energy has been found to vary by factors of 0.5 to 2.³⁴ The value of Φ is found based on a function of non-dimensional crack length (a/D) and length/width (L/D) ratios. The non-dimensional crack length is calculated by dividing the crack depth (a) by the thickness of the sample.

³³ See Book Reference. #13. Mascia, L. Thermoplastics: Materials Engineering. Applied Science Publishers Ltd, New York, 1982.

³⁴ See Book Reference. #13. Mascia, L. Thermoplastics: Materials Engineering. Applied Science Publishers Ltd, New York, 1982.

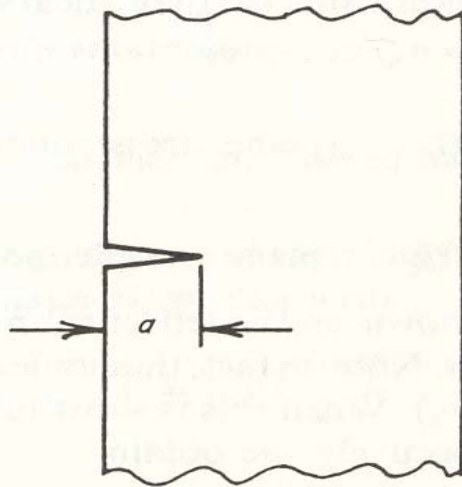


FIGURE 14: Notch dimension a.³⁵

The value of Φ is inserted into the equation $U = BD\Phi$, where U is the total energy needed to break the sample, B is the sample thickness and D is the width of the sample. By varying the width and/or thickness the above plot can be produced. The Charpy impact energy is determined by measuring the slope of the line, which is constant for all widths and thicknesses.

The Charpy impact energy of a material can be multiplied by the width and thickness of a sample to calculate how much energy the specific sample can absorb before breaking. Because this is true, a common width can be used to compute the energy absorbed at different thicknesses. The total impact energy a sample absorbs before fracture can be computed by Equation C.1 below, where U is total impact energy in J, CH_i is the Charpy impact energy of material i , B_s is the test sample thickness in cm (1.0 cm for metals, 1.27 cm for plastics), and D_s is the test sample width in cm (1.0 cm for metals and 1.27 cm for plastics).

$$U = CH_i * B_s * D_s \quad \text{Equation C.1}$$

³⁵ See Book Reference. #13. Mascia, L. Thermoplastics: Materials Engineering. Applied Science Publishers Ltd, New York, 1982.

Note that Φ is not present in this equation. The Φ that was used previously was included to compensate for the presence of the notch in the sample. Since there is not a notch in our gas tank wall, a factor is not necessary to account for the crack when estimating the energy required to break the tank wall. Thus, equation C.1 is appropriate.

A common width of 12 inches (304.8 mm) was chosen to compare the steel tanks currently used to the materials being considered for the design. Steel tanks are currently manufactured from 20 gage AISI 1020 steel that has a Charpy impact energy of 16.0 J/cm². The thickness of 20 gage steel is 0.912 mm giving it a total energy of 47.0 J for the comparison width of 12 inches. The required thickness a material must be to match the total impact energy of another material of specified thickness can be computed using Equation C.2 below, where CH_i is the Charpy impact energy of material i , CH_j is the Charpy impact energy of material j , B_i and B_j are the respective thicknesses in cm, and D_i and D_j are the respective widths in cm.

$$U_i * B_i * D_i = U_j * B_j * D_j \quad \text{Equation C.2}$$

Assuming the width is the same for each material, since the tanks being compared are the same size, $D_i=D_j$ and thus can be dropped from both sides of the equation. The total energy of the metal is shown on the left hand side of the equation, and the total energy of the material being compared is on the right hand side of the equation. The total energy of the metal can now be replaced by a total energy higher than that of the metal sample in order to determine the thickness of material needed to give the material an impact energy greater than that of the steel sample. Equation C.3 is used to compute the thickness of material needed to meet the desired total impact energy, where $U_{desired}$ is the total impact energy the material needs to have in J, B is the thickness of the material required to meet $U_{desired}$ in cm, and D_i the comparison width used for the calculations in cm (30.5 cm).

$$B = \frac{U_{desired}}{CH_i * D_i} \quad \text{Equation C.3}$$

The desired impact energy was set to 50 J so that the proposed tank wall thickness would result in the tank's impact energy being greater than the impact energy of steel tanks. The material thickness results are shown in TABLE 5 below. From the table it

can be seen that Curv®, HDPE, and Nylon 6 are attractive material options if tank thickness is a deciding factor.

Material	Charpy Impact Energy (J/cm ²)	Thickness (mm)
1020 Steel	16.9	0.912
HDPE	6.8	2.41
Nylon 6	5.2	3.15
Nylon 6 10% glass	0.5	30.95
Nylon 6 20% glass	1.7	9.65
Nylon 6 30% glass	1.8	9.11
Nylon 6/6	3.4	4.82
Nylon 6/6 20% glass	1.0	16.40
Nylon 6/6 30% glass	1.7	9.65
Nylon 12	2.4	6.84
Nylon 12 20% glass	1.6	10.25
Nylon 12 30% glass	1.7	9.65
Curv	12.0	1.37

TABLE 5: Charpy impact energies and thicknesses required to equal steel.

Abrasion Resistance

The Rockwell hardness number is the closest approximation to an abrasion resistance that currently exists. The Rockwell hardness is the ability of a material to resist indentation. A small steel ball or a sphericonical diamond is pressed into a flat sample of the material. A minor load is applied first, typically 10 kg·f. A major load of 60, 100, or 150 kg·f is applied for a specified amount of time, which is typically 10 to 15 s. The distance that the indenter penetrates the sample is correlated to determine the Rockwell hardness number. Several scales have been developed that allow the hardness number to be determined for the varying indenters and loads. The Rockwell hardness number is directly related to the strength of the material; the harder the material, the larger the hardness number. However, the ASTM standard that documents the testing (ASTM D 785) procedure states that the Rockwell hardness number is not generally taken to be an indication of a materials ability to resist abrasion. Therefore, there is not an established way to evaluate abrasion resistance.

Puncture Resistance

Another property examined was a material's ability to resist puncture. If a pointed object were to impact the tank, a rupture may occur. A gas tank materials ability to resist puncture could be important, but only in rare instances. A standard exists for a high speed puncture test (ASTM D 3763-02). The test involves a steel rod that is 12.70 mm (0.500 in.) in diameter impacting the sample in a perpendicular fashion. The specimen is clamped into place by two parallel plates. The standard impact speed is 200 m/min (7.5 mph). This test would provide valuable results. One disadvantage is that the impact speed is slow relative to typical automobile speeds. However, if a vehicle is negotiating terrain that contains debris that could potentially cause a puncture, speeds are usually reduced. Another drawback is that very few puncture tests are performed. Thus, very little data is available as to materials and their puncture test results. Also, the results of the test are not necessarily linear when compared to sample thickness³⁶. A prediction of the puncture resistance of our tanks is difficult to perform, but the test will likely be carried out after prototype tanks have been produced, so that the puncture resistance of our tanks will be known.

Flexibility

The ability of a gas tank to withstand a load without deforming or cracking was examined. ASTM D 790 provides a standard method for testing the flexural properties of plastic materials. The flexural property that is of interest for gas tanks is the flexural strength. The flexural strength is determined by placing a sample on supports while applying a load until the sample cracks or breaks. FIGURE 15 below shows a sample being tested for flexural strength.

³⁶ ASTM D 3763-02

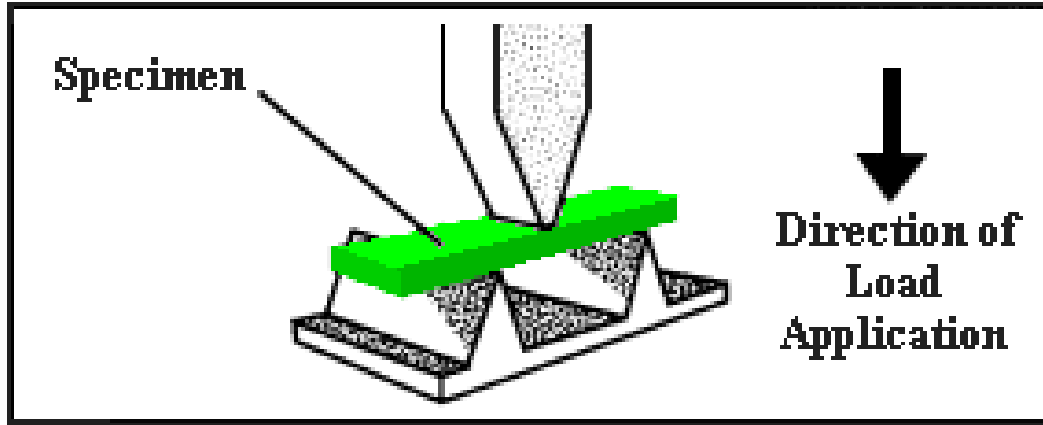


FIGURE 15: Flexural strength test.³⁷

Flexural strength is defined as the maximum stress in the outer fibers at the moment of break and is calculated using the following formula³⁸:

$$S = \frac{3PL}{2DB^2}$$

where S is the stress in outer fiber at midspan, P is the load at a given point, L is the support span, D is the width of the beam, and B is the thickness of the beam. Using this formula, the flexural strengths for each potential material taken from MatWeb, the thicknesses needed based on the Charpy impact energy to equal that of steel, and a standard gas tank size of 24.6 in. by 16 in., the force that the tank could endure without cracking is found in the table below. It was assumed that the load impacts the tank in the center, since that is the weakest point of the tank.

Material	Charpy Impact Energy (J/cm ²)	Thickness (mm)	Flexural Strength (Mpa)	Maximum Load (N)
HDPE	6.8	2.41	25	63.1
Nylon 6	5.2	3.15	85.8	370.1
Nylon 6 10% glass	0.5	30.95	140	58139.2
Nylon 6 20% glass	1.7	9.65	170	6861.9
Nylon 6 30% glass	1.8	9.11	220	7920.8
Nylon 6/6	3.4	4.82	88.4	892.0

³⁷ Flexural Strength Testing of Plastics. <http://www.matweb.com/reference/flexuralstrength.asp>

³⁸ ASTM D 790

Nylon 6/6 20% glass	1.0	16.40	180	20997.4
Nylon 6/6 30% glass	1.7	9.65	240	9687.4
Nylon 12	2.4	6.84	46.4	939.7
Nylon 12 20% glass	1.6	10.25	100	4556.7
Nylon 12 30% glass	1.7	9.65	150	6054.6
Curv	12.0	1.37	107.7	87.6

TABLE 6: Flexibilities of tank materials.

Some of the forces that the materials are able to withstand are very large. However, the thickness of the material required must be noted since many of the materials need large thicknesses to equal the impact strength of steel as was described in the discussion of the Charpy impact energies.

The flexural strengths of metals are not determined in the same manner as plastics. The only flexibility test that is performed on metals is a bend test, but the bend test cannot be used as a quantitative means of predicting actual performance³⁹. Thus, the flexural strengths of potential materials cannot be compared to that of steel. The flexural strengths can only be used as a method of comparison between potential materials.

Process Design

Rotational Molding

Rotational molding can accomplish a number of design criteria for a hollow object such as a gas tank that can never be attained with metal gas tanks.

³⁹ ASTM A 370

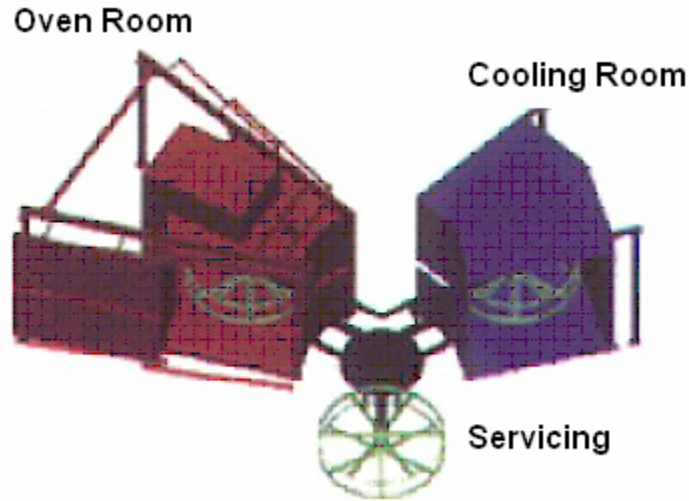


FIGURE 16: Simple top view of a rotational molding machine.⁴⁰

There are several major parts to a rotational molding machine. A typical machine will have two or three arms. Each arm holds several pre-designed molds. The molds are fixed on the ends of the arms. An oven room and a cooling room are also necessary for the heating and cooling parts of the process. The oven room moves forward when the molds of a newly loaded arm arrive. The cooling is done by spraying regular water on the molds. There is one area that is open to loading and unloading the molds. The central part of the machine rotates the arms.

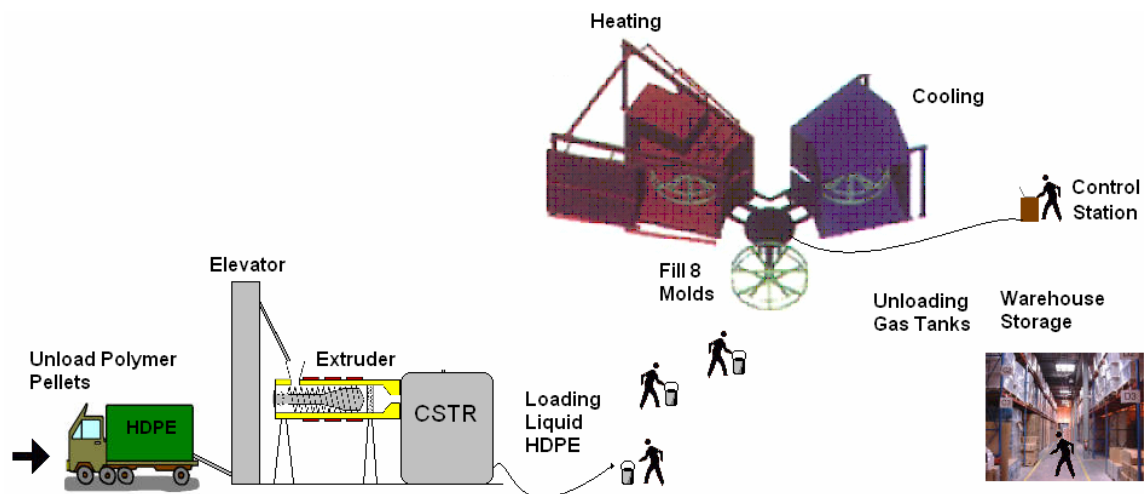


FIGURE 17: Rotational molding process flow diagram.

⁴⁰ Rotational Molding. http://engr.bd.psu.edu/pkoch/plasticdesign/Roto_Molding.htm.

The whole process is controlled by an operator using a computer processing system. The process begins by unloading the polymer pellets into a machine that dumps them into the extruder. The extruder melts the polymer and transfers all the material to the CSTR, which maintains the polymer in liquid form. An extruder is a heated screw that is used to force certain types of materials into liquid form. The following figure illustrates the main parts of an extruder.

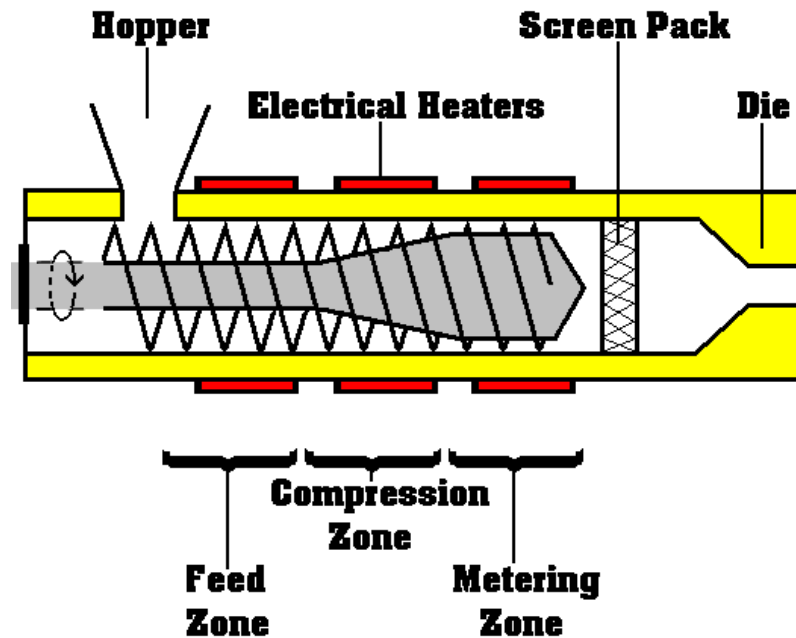


FIGURE 18: Screw extruder.⁴¹

An extruder has a hopper, which is a funnel-like part used to add the material. In this case, it is a granulated polymer. The electrical heaters on the outside of the extruder heat the polymer to its processing temperature. The flow rate can be regulated by the screen pack, which controls the pressure build up. The screen pack protects the die from any material with a diameter that is larger than allowable by the screen pack. The die shape determines the polymer exit cross section. Three general zones can be mapped out in a screw extruder: feed, compression, and metering. In the feed zone, the polymer is heated and moved to the next zone. In the compression zone, the screw is larger, which reduces the channel size, which in turn increases the pressure. The screw forces the material

⁴¹ Screw Extruders, Dies & Injection Blow Moulding.
<http://sst.tees.ac.uk/external/U0000926/POLYMER/webpag~1/intro6/intro6a.htm>.

through the extruder in one direction. The metering zone keeps the temperature and pressure constant when the polymer enters the die.

There are two to three workers that transport the polymer from the CSTR to each mold. There are eight molds on each arm. Each mold can easily be opened and the opening is large enough so that the polymer can be dumped accurately and quickly. Once this is done, the arm moves the molds into the oven. The melted resin sticks to the hot mold and evenly coats the surface. After approximately 15 minutes, the arm moves the molds into the cooling room and cools the mold and the resin. This causes the resin to coat the mold with an equal wall thickness as it cools. After approximately 15 minutes of cooling, the mold is hard and cool enough to be moved to the servicing area to be removed from the mold. Loading the polymer and removing the rotationally rotated gas tank takes 15 minutes.

Each mold is continuously rotated around both the x and y axes. This is the main secret to rotational molding's claim to producing products with constant wall thickness.

Before choosing to rotationally mold a product, information like specific chemical resistance, temperature, concentration, density, and how the product is to be used should be considered. A mold can then be made after determining the dimensions of the product. A mold is typically cast, machined from aluminum, or fabricated from steel. Frames and a clamping system will fit the individual mold sections. Each mold will have a way to easily mount to the rotational molding machine.

There are various advantages to rotational molding that make it an attractive process for producing plastic parts. For example, a fuel tank can easily be molded to make good use of all the empty space available in a tractor. This design maximizes fuel capacity and avoids any projections of the tank to the side of the tractor. It is currently not economical to do this with metal fuel tanks.

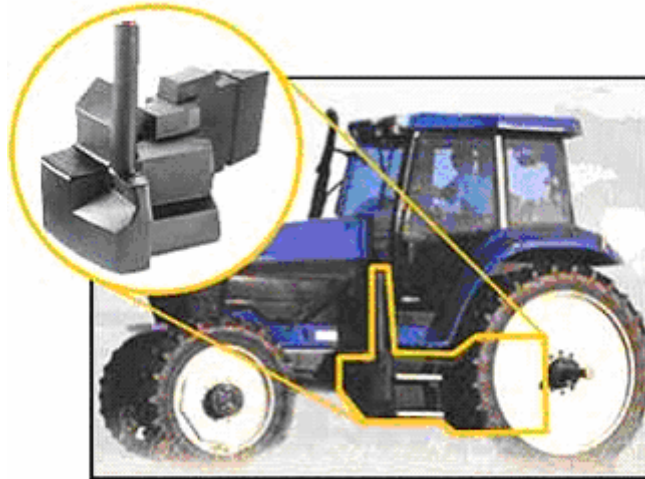


FIGURE 19: An example of a gas tank rotationally molded to fit free space.⁴²

The tanks can also be made more corrosion resistant by using additives to prevent rust or residue that clogs fuel injectors. The products made by rotational molding are seamless (one large hollow part), stress free in the corners, and require no finishing. Products can also be colored by changing the color of the resin used.

Furthermore, rotational molding can also insert into the product any extra ribs for strength or parts to the mold that would need to be added separately in a metal product. This is done by simply inserting these parts into the pre-designed mold.

Each mold for a rotational molding machine ranges from \$7,000 to \$50,000, depending on the molder designing the part and the complexity of the mold. Usually, the mold needed is designed and the specifications are submitted to a company that fits and sells rotational molding machines, such as Ferry Industries, Inc. The best machine is then fitted after accounting for such factors as the number of products produced per year, the amount of molds that fit on one arm, working days and other working times, and cost. Depending on the machine ordered, its capabilities, the year created, and other factors, the cost for rotational molding machines may be as low as \$50,000 or as high as \$250,000. If a machine were bought from Ferry Industries, the model would be a RS220 and it would cost \$183,000⁴³. Each arm would fit eight molds, and it would take 45 minutes for each arm to make a complete cycle and finish the molds.

⁴² Solar Plastics, Inc. <http://www.solarplastics.com>. 2002

⁴³ Phone conversation with Ferry Industries, Feb. 2004.

However, rotational molding cannot produce a product in large quantities without having to invest in several large machines and multiple tools. Molding cycles are very long compared to other processes. Rotational molding also requires more labor per machine than other forms of molding because each product needs to be loaded and unloaded from each mold manually after each cycle. If the product dimensions change substantially, a new mold would need to be ordered. It also requires large amounts of energy due to the large machinery needed. Furthermore, industry typically only uses polyethylene in rotational molding since there are few types of resins that can be rotationally molded. Among the other possible materials are PVC, nylon, polypropylene, cross-linked polyethylene, and plastisols.

Unfortunately, rotational molding cannot produce a multi-layer gas tank. Rotational molding can only make a one-piece hollow object so there is no possibility of fitting one tank in another. Since the plastic is formed inside a mold it is not possible to include the EVOH layer without it mixing into the polyethylene. In short, a rotationally molded gas tank would not be able to create a gas tank that allowed “near zero” emissions.

Injection Molding

Injection molding is proven production process that has been used for many decades to produce small, plastic parts.

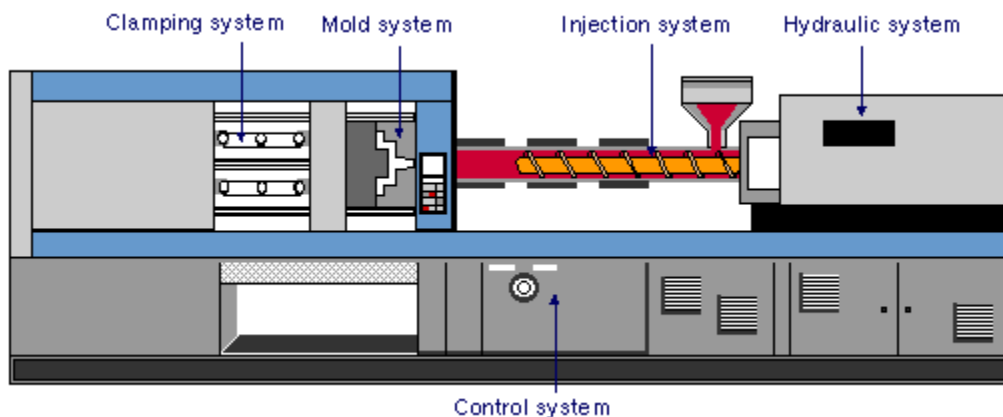


FIGURE 20: A simple injection molding system.

Starting on the right is the hydraulic system. This system is a motor which turns the screw in the injection system. Polymer pellets are poured into the funnel where they are heated to their melting point and pushed by the screw into the mold. The mold is then clamped down using high pressure to allow the hot polymer to enter. The polymer cools then the mold is opened, revealing the molded part⁴⁴.

The application of injection molding to this project is polymer would be injected into the mold of a gas tank. After the tank is made, the barrier layer can then be applied on the inside of the tank.

The thickness will be calculated from the material strength tests and the barrier layer will be found by applying the diffusion model with the appropriate permeability to determine a thickness. Each polymer will produce a different tank but an example would be that of HDPE (m.w ~ 1.1) and it would produce a tank that weighs approximately nine pounds.

Husky Injection Molding⁴⁵ is one of the leading injection molding manufacturers in the North Americas. They are based in Canada and our information comes from their sales office in Dallas.

The injection units are based on clamp forces. The clamp is the portion of the unit which, through pressure, holds the mold together while the polymer is forced in. The machines are sized by clamp forces, typical clamp forces are anywhere from 500-3000 tons of force. For example, since an HDPE tank would require a nine pound shot it will probably require clamping forces in the 2000 tons because of the large shot size.

The mold is made into the shape of the tank. Mold manufacturing can be very complicated and several variables are involved. The type of steel is important because polymers melt at different temperatures, which means the steel needs to be able to withstand different temperatures and have a low expansion coefficient. The surface needs to be prepared in such a manner that the polymer doesn't stick to the mold once the product is made. Time spent trying to remove a part results in dead time. This dead time costs the company money because wages are being paid but product is not being made.

⁴⁴ See Book Reference. #11. Rosato, Dominick. **Injection Molding Handbook**. Kluwer Academic, 2000.

⁴⁵ Husky Injection Molding Systems Ltd - www.husky.ca

Mold design is often made better through experience and empirical knowledge and each mold is custom made to the customer's specification. The price is an estimate.

The process flow diagram for a plant that revolves around the injection mold would like like this:

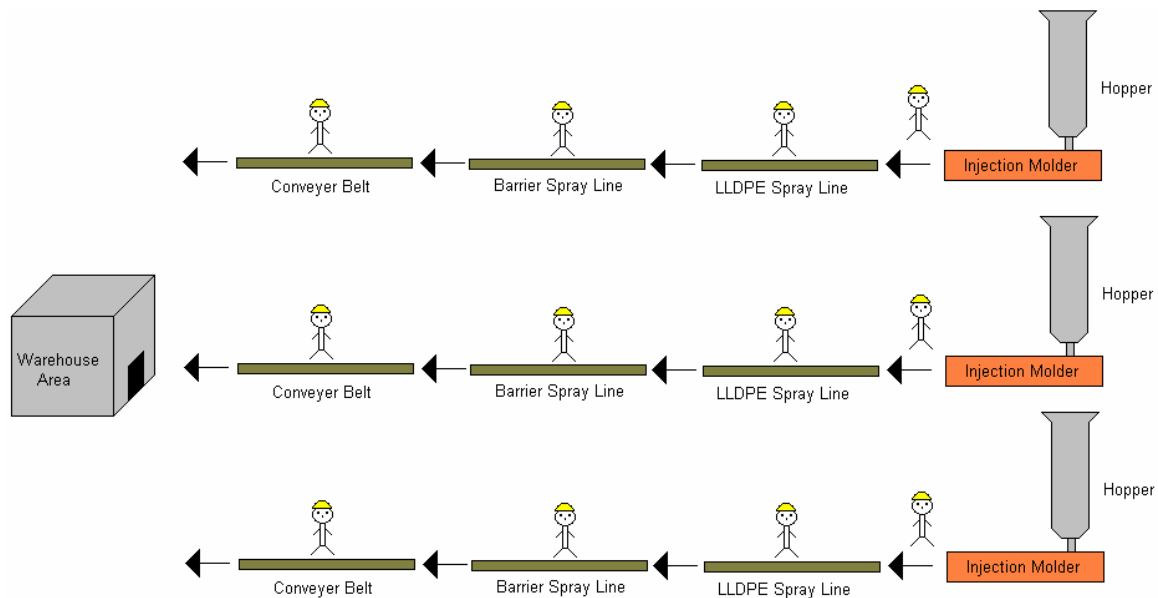


FIGURE 21: Process flow diagram for an injection molding plant.

The diagram above shows the process flow diagram for the injection molding plant. Initial estimates from cycle times (approximately 1 minute) suggest that at least three injection molding machines would be needed to meet a 500,000 tank per year capacity. With three injection molding machines working in parallel, approximately 1430 tanks are produced in a 24 hour period. The resulting tanks would then be removed from the mold and placed on a conveyer belt to be sprayed with an adhesive layer. This will allow the barrier to be connected to the wall. The tank is next sent to be sprayed with the barrier. After this a conveyer will carry the finished tanks to a warehouse where they will await distribution.

The drawback to this process is that injection molding is possible for the mass manufacturing of gasoline tanks but it would require approximately 8 machines at 3 million dollars each⁴⁶. This would result in an enormous capital investment. Additionally, the molds must be machined precisely. In order for a multiple layer tank to be created

⁴⁶ Husky Injection Molding Systems Ltd - Dallas Vendor Information- www.husky.ca

without spraying the inner or outer layers, the tank layers would need to be molded separately. This is not feasible from a quality control point of view. Due to the outrageous capital investment required and the difficulty of application, injection molding is not a practical process for producing gas tanks.

Reaction Injection Molding

Reaction injection molding is similar to injection molding in many ways but the key difference is that the polymer matrix is created within the mold. Typically two reactive liquids, such as isocyanate and polyol, are metered into a heated mold and reacted to form polyurethane, a common polymer produced with RIM⁴⁷.

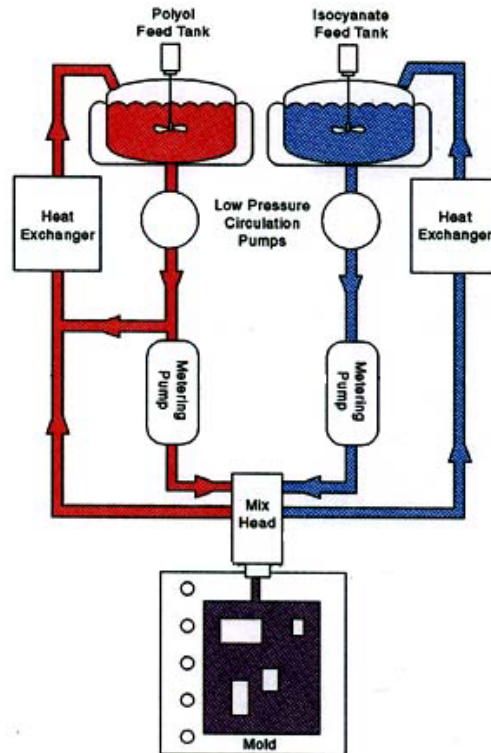


FIGURE 22: Typical RIM set up.

⁴⁷ Bayer Reaction Injection Molding (RIM) Technology. www.rimmolding.com

Two continually stirred tanks are kept at constant temperature while metering pumps extract fluid from them. Metering pumps are very exact pumps which can withstand high temperature and viscosity⁴⁸. The metered material is then sent to a mixhead where the materials are thoroughly mixed before being injected into the mold. The mold is usually kept at constant temperature, because a certain temperature is needed for polymerization to take place. The entire process takes between 1 and 2 minutes with the product ready when the mold is opened.

The application of RIM to this project is that a proper isocyanate/ polyol combination can be used to produce high strength polyurethane. The advantages of RIM to injection molding are that the unit is cheaper to set up because of the lower temperatures/ pressures, is easier to maintain because there is no extruder, and is more user friendly for maintenance. The quick cycle times also make this process feasible and applicable for mass producing polymer gas tanks.

There are some drawbacks in the consideration of this process. First is that polyurethane needs additives for strength enhancements and additives are added to the system for quick release. These are patented techniques and royalties would need to be paid just to use them. Secondly, epoxy makes for an attractive alternative but an epoxy system would need to be custom built. This is expensive and servicing such a system would not be an easy task. Also, the epoxy/ curing agents would need to be carefully formulated and monitored. This involves additional R&D which means more capital is needed.

The process flow diagram for a plant using reaction injection molding would be similar to the one found below:

⁴⁸ Neptune- VP-99V-Pumps- PDF

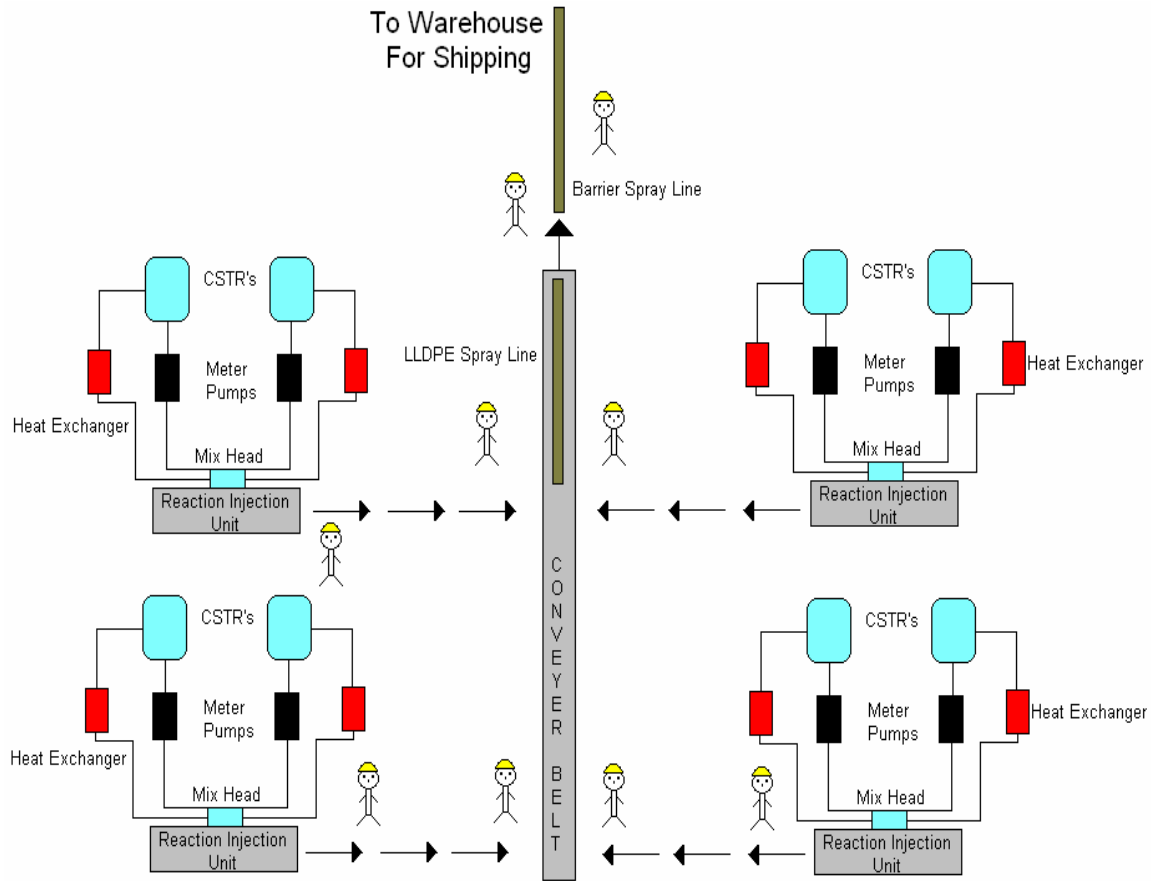


FIGURE 23: Flow diagram for reaction injection molding.

The process is similar to that of injection molding with the main difference that large holding tanks would supply each CSTR with polyol when running low to keep the production going. Once the tanks are made in the mold they are removed and placed on a conveyer belt to be sprayed with LLDPE and the barrier coating. After this the tanks are then sent to a warehouse where they will wait for shipping.

Stamping

Stamping is a process used to form objects from pre-formed sheets. The sheet to be formed is placed over a mold and then forced by a hydraulic ram with a stamp on the end to conform to the shape of the mold. For polymers, the sheets are first heated to the process temperature and then stamped. The polymer is held at the process temperature while being stamped by heating elements located in the mold patens (sections of the mold). Stamping is advantageous to use because it is simple and fast. Typical cycle

times range between 45 and 90 seconds. This includes the time for removing the formed sheet and replacing it with an unformed sheet.

For the purposes of this project, the required stamp machine will need to be capable of holding a sheet three feet by four feet (based upon rectangular 17 gallon tank), be capable of mold temperatures greater than 250°F, and have a ram with a 150 ton rating. Heating and maintaining the mold temperature can be performed by either electric elements within the patens, or by heat transfer from a fluid through tubes mounted within the mold walls. It is easier and more convenient to use electric patens, because the process is not very complex and heating and cooling a fluid would be more expensive than electricity, since little heat integration is possible within the process. The electric patens would also provide a constant mold temperature without complex controls as would be needed in the use of a hot fluid.

Stamping would require the production of polymer sheets from polymer pellets for most composite materials. The process flow diagram for the polymer sheet forming section is shown below in FIGURE 24:

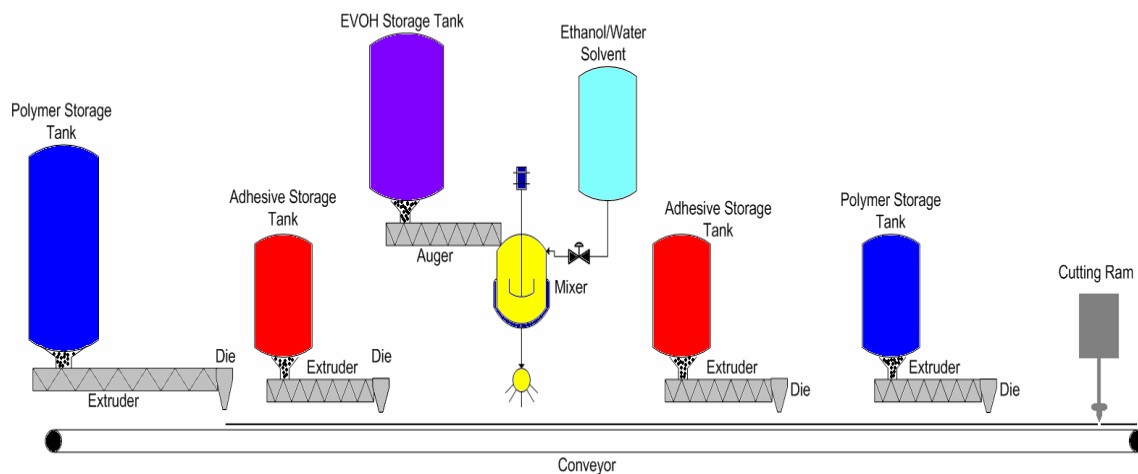


FIGURE 24: Sheet forming section of the plant.

The polymer would be stored in a storage tank in the form of pellets. An extruder then heats the polymer pellets into a liquid form and moves the liquid polymer to the die. A die is a tool used to form liquid polymers into fibers or sheets (picture is shown below in FIGURE 25).



FIGURE 25: Die tool.

The die sprays the polymer onto a moving conveyor belt forming a continuous sheet of polymer of specified width and thickness. The die contains small holes through which the polymer is forced, forming polymer fibers. As the polymer is laid onto the conveyor belt, the sheet is formed. After the structural sheet of polymer has been formed by the die, the sheets pass under another die that lays an adhesive layer onto the sheet. After the adhesive layer has been formed, the sheet is sprayed with a barrier layer of EVOH. The sheet then passes under another die, which adds an adhesive layer. Finally, the sheet receives another structural layer. The cooled polymer is then cut into sheets of desired length by a 50 ton hydraulic ram equipped with a cutting blade. The sheet forming section of the plant will produce sheets at a faster rate than the stamping section of the plant. The sheets coming from the sheet forming section not being immediately used by the stamping section will be held in a holdover area. This also means that the sheet forming machinery will not be operating continuously. One laborer will work at the end of the conveyor to stack the sheets onto pallets to be stored in the holdover area. The next section in the process is the heater and stamping section. One laborer will place the sheets on the conveyor to go that leads to the heater section (shown in FIGURE 26 below).

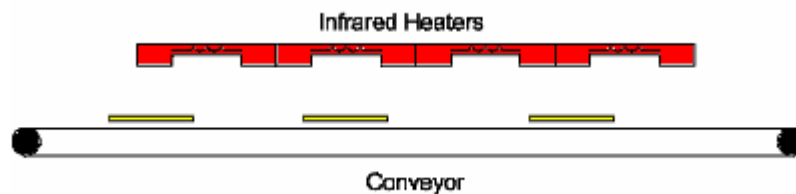


FIGURE 26: Infrared Heaters.



FIGURE 27: Stamping machine.

After the sheets exit the heater section, they are taken to the stamping machine to be formed into the desired shape by the operator. After the parts have been formed, the operator will place them on the conveyor leading to the assembly section of the plant. The halves are assembled by heating the flanges on each side, pressing the halves together, and then allowing the pressed halves to cool. After the seam has cooled, the two halves are then riveted together using steel rivets to provide extra support. Two laborers are needed for the assembly section; one assembly section handles two stamp sections. In addition, a laborer will be needed to transport the assembled tanks to storage.

Stamping is advantageous over other methods of processing that might be used for making gas tanks for several reasons. Stamping is simple; no complex procedures or machinery is required. The actual stamping process does not require much electronic control or instrumentation. The stamp can be run by one operator with the help of two laborers for changing out the sheets being stamped. Stamping is quite fast compared to other processing methods with cycle times of 90 seconds. Due to the fast cycle times, stamping requires fewer machines than other processes to produce the same number of tanks.

Stamping equipment requires little maintenance compared to other processing equipment. Stamping does have disadvantages as well. The design cannot be made seamless with stress free corners. Not all polymers are able to be deformed without

damage, so the number of polymers that can be used is decreased. The tank shapes cannot be too complex. If the shapes become too irregular the polymer sheets cannot be shaped properly without damage and loss of mechanical properties. Both a top and a bottom piece would have to be formed for each tank produced. The formation of polymer sheets using an extruder/die setup must be controlled quite strictly. This requires more control and instrumentation than the stamping machine requires. Dies and extruders are also quite expensive and require a large amount of maintenance to keep them functioning properly. The setup and operation of a die/extruder processes requires expertise, which results in higher labor costs.

Blow Molding Process

Blow molding has several advantages, similar to other plastic molding techniques. This process usually uses commodity materials such as PVC, polystyrene, polypropylene, LDPE, and HDPE.

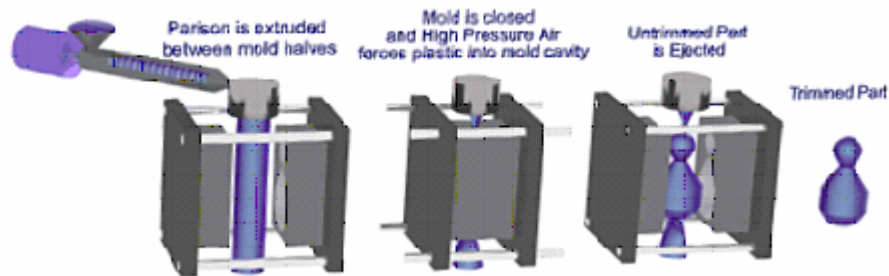


FIGURE 28: Thermoplastic blow molding.

The figure above shows the blow molding process. Plastic pellets are used as the inputted material in this process. An extruder forces the plastic pellets into the mold by heating the plastic and using pressure as the main driving force.⁴⁹ The actual blow molding happens between two molded halves. The mold is actually two separate parts that, upon closing, the inside cavity is the desired product shape. After the parison is extruded, the mold is then closed and then compressed air forces the plastic into the mold cavity. The part is then cooled and ejected once it has hardened. The part is then trimmed

⁴⁹ See Appendix. Screw Extruder.

to meet specifications. The whole process uses compressed and chilled air, electricity, and cooling water.

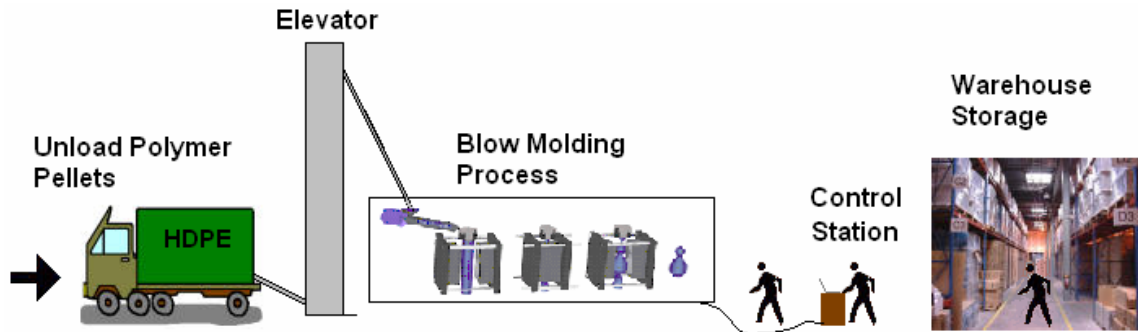


FIGURE 29: Blow molding process flow diagram.

This process, unlike rotational molding, does not require a CSTR. The reason for the lack of CSTR is because it is a continuous process, so the polymer pellets would only require storage after they are unloaded. After the pellets are extruded, the blow molding machine creates the trimmed part. The trimmed part is then compiled and taken back to the warehouse. In total, only three workers are needed for this. Two skilled workers are needed to maintain the machine and control the process. The worker in the storage warehouse takes care of the product transportation and storage in the warehouse.

There are important factors one should consider when designing an extrusion blow molder:⁵⁰

- Polymer viscosity at high & low shear rates
- Melt strength (important for uniform wall thickness, no holes)
- Strain recovery (MW & Distribution)
- Crystallization rate (slow rate desired)
- Thermal properties (thermal diffusivity, thermal conductivity, specific heat, etc.)

Compared to rotational molding and reaction injection molding, the equipment cost is competitive.⁵¹ The production rate is moderate to high. For example, the production rate is higher than that of rotational molding, which makes blow molding more applicable for large production volumes than rotational molding. The large production is largely due to the fact that the extrusion part of the process is continuous

⁵⁰ Blow Molding. <http://www.engr.uconn.edu/cheg/polymer/blow.htm>

⁵¹ See Appendix. Financial Evaluation for Processes.

and the rest is cyclic. All the parts molded with blow molding have high strength to weight ratio compared to other plastic processes.

Materials Selection Discussion

Materials selection is dependant on many factors such as process choice, money and most importantly material strength. The logic behind this procedure is that before a material can be considered, the process needed must be able to mass produce gas tanks. So a list of processes must be made. From this list of processes, all the materials that can be are included for each process. These materials are next evaluated using the Charpy Impact energies in comparison to steel's Charpy Impact energy. The materials that pass this test are then evaluated with their respective process.

Process Selection

Five processes were found that could reliably mass produce polymer gas tanks. The five are reaction injection molding, injection molding, rotational molding, blow molding and stamping.

Reaction injection molding is a very popular method for mass producing plastic parts because of the low pressures and temperatures required for the reaction to occur. The drawback to this process are the royalties for patents. The patents are numerous because of the need for special additives for quick release, additives to decrease brittleness, additives for strength enhancement, and so on.

Injection molding is attractive because of the speed and simplicity of the process. Its drawbacks are that high temperatures and pressures and usually involved in the process. The drawback to this process is the large expense for the injection molder. A nine pound shot is very large compared to typical 12-24 ounce shots used in industry.

Rotational molding is unique in that it can make several parts at once because of the multiple arms the machine uses. Its major drawback is that the cycle time in rotational molding is very large compared to that of the other processes. Because of this large cycle time multiple machines would be needed working side by side which would raise the initial capital investment.

Blow molding is another popular technique and is used by a few companies in industry to make gas tanks. Visteon, a Ford subsidiary, uses blow molding to make

polymer gas tanks for a few of its models. Again, like reaction injection molding, their technique of blow molding is patented. What makes this process difficult is the control over the wall thickness of the gas tank. The gas tank walls need to be exact in their thickness and large variations are not allowable. Their technique for this is patented and not readily disclosed.

Stamping is a simple and fast technique that requires little supervision or utilities. As long as the material is formed into sheets it can be heated, then pressed into the shape desired. The resulting halves can be riveted together to form the gas tank.

Material Selection

Each process has certain materials that can be used to make the gas tank. Reaction injection molding typically uses polyol and isocyanate to make polyurethane and epoxy resins. Injection molding can take materials such as nylon, polyethylene, and polypropylene. Rotational molding and blow molding can also take the same materials as injection molding. Stamping is versatile as well and can also work with these materials provided that they are malleable enough when heated. Since the processes can all work with many kinds of materials the Charpy Impact test will be used to eliminate some candidates. A table showing material and applicable process is shown below.

Process	Materials
Blow Molding	Polyethylene, Polypropylene
RIM	Polyurethane, Epoxy
Injection Molding	Nylon, Polyethylene, Polypropylene
Stamping	Nylon, Polyethylene, Polypropylene, Curv
Rotational Molding	Nylon, Polyethylene, Polypropylene

TABLE 7: Materials compatible to each process.

Charpy Impact Energy

The Charpy impact energy simulates the impact a tank undergoes. As was shown earlier, the three best materials for a structural layer are Curv®, high density polyethylene, and nylon 6. The impact energies and the thicknesses required to equal those of steel are found in the table below.

Material	Charpy Impact Energy (J/cm ²)	Thickness (mm)
Curv	12.0	1.37

Nylon 6	5.2	3.15
HDPE	6.8	2.41

TABLE 8: Charpy energy and needed thickness.

It can be seen from the figure that Curv® easily outperforms all other materials when it comes to thickness vs. strength. Another property that can be looked at that would influence selection is the softening temperature. A higher softening temperature indicates a wider range of operational temperature. The material is able to withstand more heat without compromising its integrity.

Materials	Vicat Softening Temperature (°C)
HDPE	110
Curv	175
Nylon 6	170
Nylon 6 10% glass	220
Nylon 6 20% glass	220
Nylon 6 30% glass	220
Nylon 6/6	190
Nylon 6/6 15% glass	230
Nylon 6/6 20% glass	230
Nylon 6/6 30% glass	230
Nylon 12	140
Nylon 12 20% glass	170
Nylon 12 30% glass	170
Ethylene Vinyl Alcohol	173
Kynar	138
Linear Low Density Polyethylene	107

TABLE 9: Vicat softening temperatures.

Nylon exhibits high softening temperatures which makes it harder to work with than Curv®. Higher temperatures require higher pressures in an injection molding machine, higher utility use for mold heating in a rotational molding machine and a blow molding machine. However, this is not reason alone to eliminate materials from the list. Since all of these materials equal steel in strength with the appropriate thickness, a financial analysis needs to be made to determine which material is cheaper to process.

Financial Analysis

A table of the price each tank will cost (taking into account strength only) according to the material it is made of is given below:

Polymer	Cost (\$/tank)
HDPE	3.96
10% Nylon 6	38.47
20% Nylon 6	12.31
30% Nylon 6	15.66
Nylon 6	2.39
20% Nylon 12	14.23
30% Nylon 12	16.78
20% Nylon 6,6	28.23
30% Nylon 6,6	19.88
Nylon 66	4.45
Nylon 12	6.43
Curv ®	5.26

TABLE 10: Material costs per tank

From the table it can be seen that Nylon 6 is the cheapest tank followed by Curv® and HDPE. A comparison between the three structural materials plus the two diffusion materials is made below.

Material	Diffusion Thickness (mm)	Charpy Impact Thickness(mm)	Price Per Pound
Nylon 6	0.566	3.15	3.21
HDPE	7825	2.41	0.51
Curv	8607	1.37	1.87
Kynar	0.132	7.46	8.45
EVOH	0.033	41.31	2.65

TABLE 11: Comparing thickness for diffusion, Charpy Impact, and price.

Above is a comparison between the thicknesses needed to comply with EPA emissions and steel's structural properties. Price is also included to make distinctions better. There are a few comments that can be made from this table.

- EVOH can not be used as a structural enhancer
- HDPE and Curv can not be used for diffusion
- Kynar is expensive when compared to EVOH

- Curv is the best structural enhancer
- EVOH is the best diffusion enhancer
- Nylon is more expensive than Curv or HDPE

From these points it can be said that EVOH and Curv make the best combination, both from a technical and financial point of view. Because EVOH is now the diffusion barrier an additional layer will be needed between the EVOH and the gasoline to prevent swelling from oxygenated gasoline. This forces the system to have more than 2 layers. The additional layers will alter the process considerations because not all the processes can handle multiple layers. Using this new design information and a profitability analysis on the remaining process options, a choice can be made. The following section outline the method used to carry out the financial evaluation.

Financials

Economic Evaluation

An economic evaluation was performed for each process using the best material for each respective process. For reaction injection molding and blow molding, the most suitable material, the cheapest material that can be used effectively, was found to be high-density polyethylene (HDPE). Epoxy was the material used with reaction injection molding. Curv® was the best material found for the stamping process. In addition, an evaluation of the stamping process using HDPE was considered, so that stamping could be compared to the other processes using a common material. It was also necessary to compare HDPE to Curv®, which could only be done with the stamping process.

The Peters and Timmerhaus method for economic evaluation was used for cost and profit estimation. A spreadsheet was created for each process to outline specific costs and economic potential. Each sheet was customized for each process in order to obtain the most accurate results. The following six sections document important points in the economic spreadsheets. Finally, descriptions of the method used for location evaluation as well as location specific economic evaluation are provided.

Capital Investment Estimation

The spreadsheet was originally set up to calculate all of the direct and indirect costs based on the value input for purchased equipment. The sheet was modified to more accurately depict our situation. The building and construction costs for each process were input directly. These were estimated by determining the square footage required to operate the machines, to accommodate office space and warehousing. The total square footage required was multiplied by \$82/sq. ft.⁵² The building and construction costs included in the *82/sq. ft. are buildings, construction expenses, legal expenses, and contractors fees. The remaining direct and indirect costs were estimated based on a percentage of the purchased equipment. The percentages were adjusted from the suggested values in order to accurately simulate our processes. The working capital was also estimated as a percentage of the purchased equipment. The fixed capital investment was found by summing the direct and indirect costs. The total capital investment was calculated by adding the working capital to the fixed capital investment.

Materials and Labor Cost Estimates

The value of all products, as well as the cost of materials and personnel, was calculated. For the products section of the spreadsheets, the types of tanks that are produced, the sale price per tank for each type, and the annual production of each process in millions of tanks per year, were defined. The materials section requires inputs for the unit cost of each raw material used and the yearly quantity of each material needed. These values varied based on the tank design, and were limited to the price and annual consumption of the actual materials used in the tank. Labor costs were dependent upon the number of operators per shift, the number of shifts per day, the hourly wages for operators, and the Engineering News Record (ENR) skilled labor index⁵³. The number of operators necessary per shift depends on the process type and plant setup. It was assumed that the plants operate with three shifts per day. Operator wages varied regionally depending on the given workforce supply and the demand; the default values

⁵² 3C Design Company, Architecture firm located in Norman, OK

were based on the national average of ENR's wage index. This was a reasonable estimate for process/material comparison.

Utilities Cost Estimation

The utilities spreadsheet required values for the amount utilities used on an annual basis. These values differed from process to process and were determined for each plant design. Default costs for each utility were provided. Although the actual values varied depending on plant location, the default values were reasonable for initial cost estimates to perform process/material comparisons.

Depreciation

The depreciation spreadsheet contains values for the annual depreciation factor for a number of depreciation methods. The method we used is 5-year MACRS (modified accelerated cost recovery system). Since different depreciation methods could be selected (restricted to those allowed by the IRS), different methods can be tried for each plant setup so the most beneficial is eventually used. Five-year MACRS is the method used for all sheets since MACRS is the industry's most widely used form of depreciation.

Annual Total Product Cost Estimate

This worksheet calculates the total annual cost needed to produce fuel tanks without any depreciation factored in. Included in this sheet were costs such as, insurance as a percentage of FCI and plant overhead as a percentage of the sum of labor, supervision, and maintenance costs. Percentage estimates for each of these items were provided as defaults and were used to compare processes/materials. The suggested percentages were altered for each process. The labor costs were transferred to this sheet from the previous calculation that was performed. The distribution and selling cost was entered directly. The distribution and selling cost that was used to evaluate and compare processes and materials was taken from the average shipping costs from our potential

⁵³ McGraw-Hill Construction ENR - Cost Indexes
<http://enr.construction.com/features/conEco/costIndexes/mostRecentIndexes.asp>

plant locations to our potential customer locations. The potential plant and customer locations are discussed later in the location evaluation section of the report.

Financial Evaluation Estimates

Values for product cost, FCI, working capital, labor cost, depreciation factors, etc... that were calculated in previous spreadsheets were included in this section. Given the lifetime of the project, indicators of its economic feasibility including ROI, payback time, net return, NPW and discounted cash flow rate were calculated by considering the time value of money. These values allowed easy determination of whether any more time and money should be invested in a given initial plant design or if the project should be continued at all.

For each process and material evaluated (blow molding HDPE, reaction injection molding epoxy, stamping HDPE, stamping Curv®), the following assumptions were made:

- Plant production capacity of 500,000 tanks/year. This capacity is roughly equal to the number of 17 gallon gas tanks GM produces per year or the total of similar Honda and Nissan gas tanks (13, 17, and 20 gallon).
- Tanks are sold for \$47.00/tank. The competition's selling price is estimated to be \$53.00. The selling price of \$47.00 was chosen in order to maintain a return on investment of 15% and to undercut the competition.
- Minimum acceptable rate of return for NPW calculations (discount rate) is 3.69% annually. This value is equal to the annual yield of a 10-year US federal treasury bond on 03/11/2004
- Project life of 10 years

All additional necessary information was customized. It should be noted that these process/material comparison are location independent. Values that varied geographically (labor wages, shipping costs, building costs, etc...) were calculated with average indices and standard values. This is acceptable for the economics sheets used to compare processes and materials since the location specific values should vary similarly for each

process/material. The economic estimates for each process are given in TABLE 12 below:

Process	TCI / \$ 1e6	ROI (%)
Blow Molding HDPE	13.960	7.00
Reaction Injection Molding Epoxy	5.893	-32.10
Stamping Curv	3.651	15.8
Stamping HDPE	18.610	-7.81

TABLE 12: Economic values for process comparison.

Stamping Curv® is clearly the best investment with a return on investment far greater than any other process. Though the NPW is not significantly greater than blow molding HDPE, the capital investment is much less so potential losses are reduced. This was due largely to the fact that Curv® comes in preformed sheets, in the specified thickness, ready for stamping. This drastically reduced equipment costs and caused the process to be more profitable. Additionally, the Curv® is extremely strong so only a small amount of material is needed to achieve the desired strength.

Location Evaluation

The location of our plant was chosen by considering the location specific costs for labor, building, construction, utilities and the transportation costs. Thirteen cities were considered as possible plant locations. These cities were chosen for their large labor pools and access to transportation, both trucks and trains. Five locations were considered as possible delivery points. These potential customer locations are areas where large amounts of automobiles are assembled. The possible plant and delivery locations are listed below:

- Potential Plant Locations
 - Atlanta, GA
 - Birmingham, AL
 - Chicago, IL
 - Cincinnati, OH
 - Cleveland, OH
 - Dallas, TX

- Detroit, MI
- Kansas City, MO
- Minneapolis, MN
- New Orleans, LA
- Pittsburgh, PA
- St. Louis, MO
- Toronto, ON
- Potential Delivery Sites
 - Birmingham, AL
 - Chicago, IL
 - Detroit, MI
 - Jackson, MS
 - Columbus, OH

The Engineering News Record provides indices for all labor, building and construction costs. The costs originally calculated for each process were based upon the average indices. For each location, the location specific costs were found by multiplying the original cost by the ratio of the location specific index to the national average index. Shipping costs from each potential location were also considered. Mapquest.com was used to find values for distances from each of our potential building sites to each of the five assembly locations. JB Hunt and Burlington Northern Santa Fe were contacted to estimate the cost to ship one truckload one mile via both truck and train. Assuming that each assembly plant receives approximately the same number of gas tanks and that a truck can carry roughly 90 gas tanks, the average cost to ship one gas tank was found by multiplying the average distance from a potential factory site to the assembly plants by the cost to ship one truckload one mile and dividing by the 90 gas tanks that can fit in a truck. This average value is then multiplied by the annual gas tank production to find the annual shipping cost for each location. Once these location specific costs were input into the spreadsheets used to model the financials of the process, the optimal location could be found. The location with the best net present value and the largest return on investment

was chosen to be the optimal location. The net present values and returns on investment for each potential location are listed in the table below.

Location	Tank Price	TCI (10⁶)	ROI (%/yr)	NPW (10⁶ \$)
Atlanta	\$39.00	3.162	19.4	4.05
Birmingham	\$40.00	3.269	17.0	3.55
Chicago	\$52.50	3.97	16.9	4.34
Cincinnati	\$44.00	3.551	15.2	3.38
Cleveland	\$49.25	3.743	14.9	3.41
Dallas	\$43.00	3.094	15.5	2.75
Detroit	\$51.50	3.871	17.6	4.45
Kansas City	\$52.00	3.69	17.1	3.94
Minneapolis	\$58.00	3.89	15.3	3.53
New Orleans	\$40.50	3.065	15.9	2.92
Pittsburgh	\$48.00	3.597	18.0	4.19
St. Louis	\$50.00	3.78	14.9	3.44
Toronto	\$57.50	4.062	15.7	3.89

TABLE 13: Location comparison.

The optimal location was found to be Atlanta, GA. Atlanta was chosen because it allowed a return on investment of at least 15%, while allowing for the lowest gas tank selling price. The cheapest price provides the greatest competitive advantage. Even though Birmingham and New Orleans offered similar selling prices, Atlanta resulted in the greatest net present value.

This method of determining the optimal location is not the best method possible. The factor that prevents this method from being an exceptional way to evaluate potential locations is the transportation costs. The transportation costs greatly affect the profitability of our process, and choosing the best location is crucial. This method made the assumption that each of the five potential customer locations received an equal number of tanks per year. This simplification will unlikely occur in a real situation. A better way to evaluate potential locations would be to include location in an evaluation of risk and uncertainty. The inclusion of location, while considering risk and uncertainty, is discussed further in the Risk and Uncertainty section of this report.

Final Tank Design

Target Design

The final design of our gas tank completely depends on the contract or business deal we obtain. If our target companies accept our offer, we can then proceed to obtain the gas tank design they need. Once we know their specifications and dimensions, we would be able to modify our equipment to produce a gas tank that meets their needs. We would be able to meet our customer's need according to the capabilities of the type of process chosen to produce the plastic gas tank.

For the sake of illustration, it is assumed that Honda accepts our offer and provides us with the gas tank design they need. The 2000 Honda Accord will be used for simplicity and because of the availability of this information. The figure below shows a gas tank for a 2000 Honda Accord.

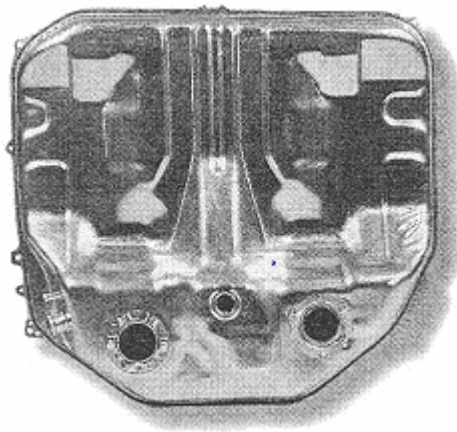


FIGURE 30: Targeted actual gas tank for a 2000 Honda Accord.⁵⁴

The dimensions for this gas tank would be 30.25 inches long, 27.5 inches wide and 9.875 inches high. It would have a capacity of 17 gallons, or 63 liters. Two straps and several O-rings would have to be purchased by the automobile manufacturer.

As mentioned, the dimensions for gas tanks vary according to company, car, year, and other factors; even such factors as the use of fuel injection or not may slightly. Honda Accords and Civics will vary from 30 to 36 inches in length, 22 to 28 inches in width,

and 7 to 10 inches in height. When all the companies are considered, the length may vary from as low as 15 to as high as 40 inches, the width may vary as low as 15 to 28 inches, and the height may vary as low as 6 inches to as high as 13 inches.

The final gas tank will have five layers of materials. The figure below illustrates these layers and their order.

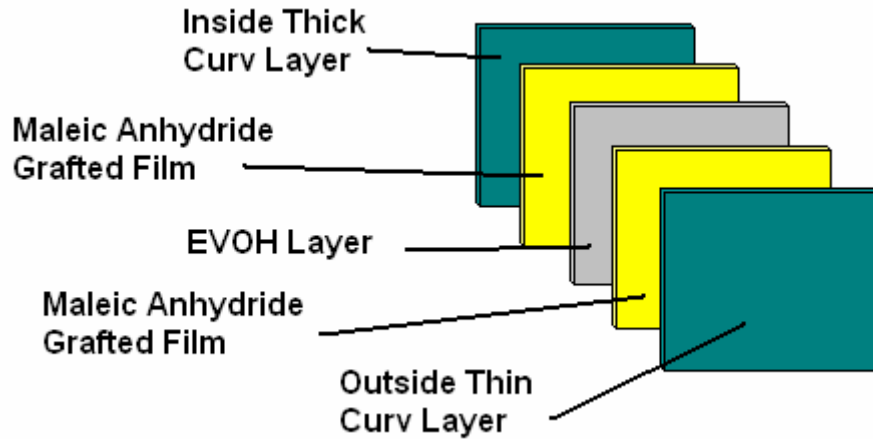


FIGURE 31: Layers of the gas tank.

After considering all the materials in regards to the thickness of the tank wall, diffusion, impact strength, and material costs, the optimum material to use for the structure was Curv®. The inner layer is 1.4 mm of Curv®, which provides the structural support for the tank. However, with only a 1.4 mm thick wall of Curv®, the diffusion losses are too great to meet EPA emission regulations. In order to meet the upcoming zero level emissions standards, a 140 micron (or 0.14 mm) layer of ethylene vinyl alcohol was used as a diffusion barrier on the inside of the tank. A layer of maleic anhydride was used as an adhesive to bind the EVOH layer to the Curv® structural layer. This material is grafted onto the Curv® by the company that sells us the Curv® sheets. A 0.3 mm layer of Curv® was added on the outside to protect the EVOH layer. The outer layer was added to protect the EVOH layer from the elements as well as abrasion. The 0.3 mm thickness was chosen because it is the minimum thickness in which Curv® is available. Using this five layer structure the total thickness of the tank was about 1.84 mm with a diffusion rate less than the zero emissions level regulation of 0.35 g/day. The maleic anhydride layers are necessary for the EVOH layer to adhere to the Curv®.

⁵⁴ 2000 Honda Accord Gas Tank. Page 159. 1998 Gas Tank Catalogue. American Designers.

Since the final gas tank cannot be determined until a contract is determined, a basic gas tank shape was used to determine the cost of each gas tank. The tank size used for computing prices was a 17.0 gallon tank standard to several makes and models. Although the Honda model could have been used, this was done to reduce the complexity of the calculations. Ultimately, it does not matter because the same sample gas tank was used in every process to determine their profitability. The outer dimensions of the tank are shown in FIGURE 32, where W is the width, L is the length, and H is the height.

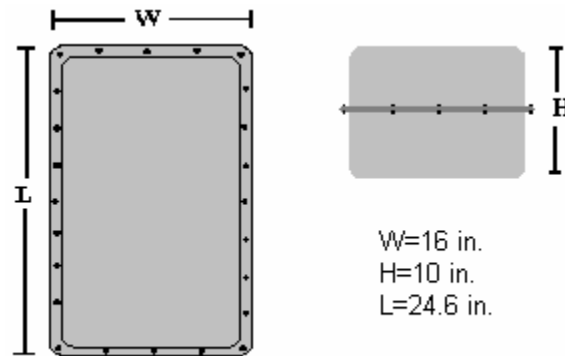


FIGURE 32: Tank dimensions used to calculate cost.

The black dots seen in the middle image represent the rivets used to add strength to the tank seam. The tank seam is represented by the darker gray line in the image furthest to the right. The seam is sealed by heating the flanges on each tank, pressing the flanges together and then allowing them to cool. Since Curv® is made of polypropylene, a good seal can be achieved using this method. The rivets are 3/16 inches in diameter and are made of steel. A rivet is placed every 3 inches along each side of the tank and every 3.2 inches along each end of the tank. Silicone is used on the outside of the seam to prevent moisture and foreign materials from collecting and building up. The total weight of the tank is approximately 6 lbs. The raw material cost of each tank is \$11.90; this includes the rivets, maleic anhydride, EVOH, and Curv®.

Contracted Tank Design Procedure

There is a procedure that will be followed in order to design and produce a plastic gas tank. The figure below illustrates this procedure.

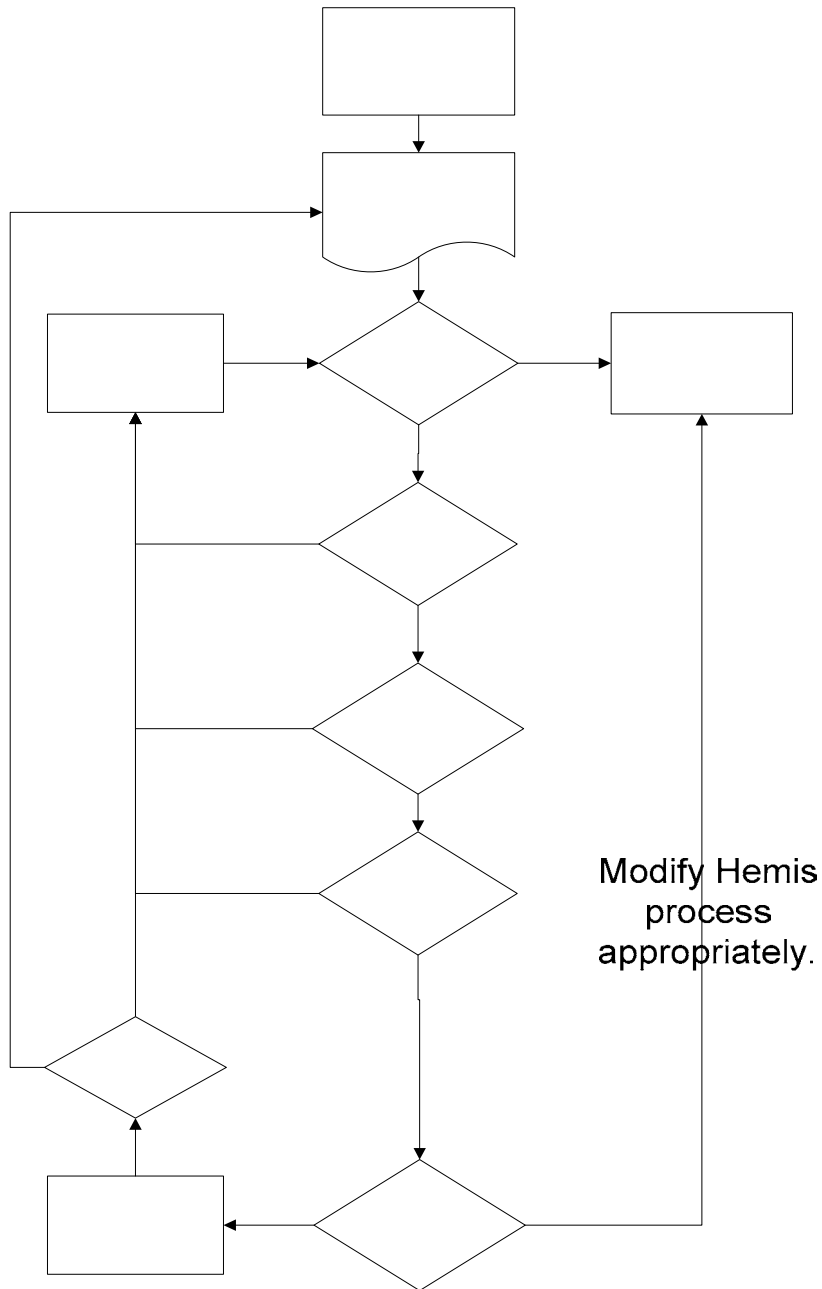


FIGURE 33: Procedure for correct gas tank design.

The procedure is straightforward, and depends on such factors as diffusion, strength, and dimensions. In case the factor that needs to be changed is not indicated in the procedure, measures are taken to identify it. If more information is needed to modify this new variable, it can be requested from the company, in this case company "A."

Diffusion can be modified by adjusting the amount of EVOH layer. Strength can be adjusted by increasing the thickness of the CURV material. The dimensions of the gas

YES

YES

tank, including any holes and specific markings, can be adjusted by changing the mold or the stamp being used. So, these variables are easily adjusted.

Final Process Design

The optimum process was found to be stamping Curv®. Stamping with Curv® differs from the stamping process presented earlier. Curv® comes in preformed sheets, thus the need to form sheets of polymer is no longer necessary. Because polymer sheets no longer need to be formed, the equipment needed to form the sheets was no longer required. The heating, stamping and assembly sections will remain the same as was described in the process design section, but the sheet forming section of the process is no longer needed.

To meet the “zero-emission” standard, a minimum of 35 microns of EVOH must be included in the fuel tank wall. Our tank design uses a 140 micron thick layer of EVOH. The additional diffusion barrier thickness is used as a safety factor since any number of factors could contribute to irregularities in the thickness applied and less than 35 microns would result in our gas tank failing to meet US government imposed emissions standards. A number of similarly designed tanks made by Visteon and Ford use EVOH layers roughly 160 microns thick, through we determined that 140 microns would be sufficient.

The EVOH is applied to our tank via pressurized spray system. To prepare the EVOH for spraying, it must be mixed with a solvent containing 80% ethanol / 20% water. The mixture should be 60 wt% EVOH pellets and 40 wt% solvent.

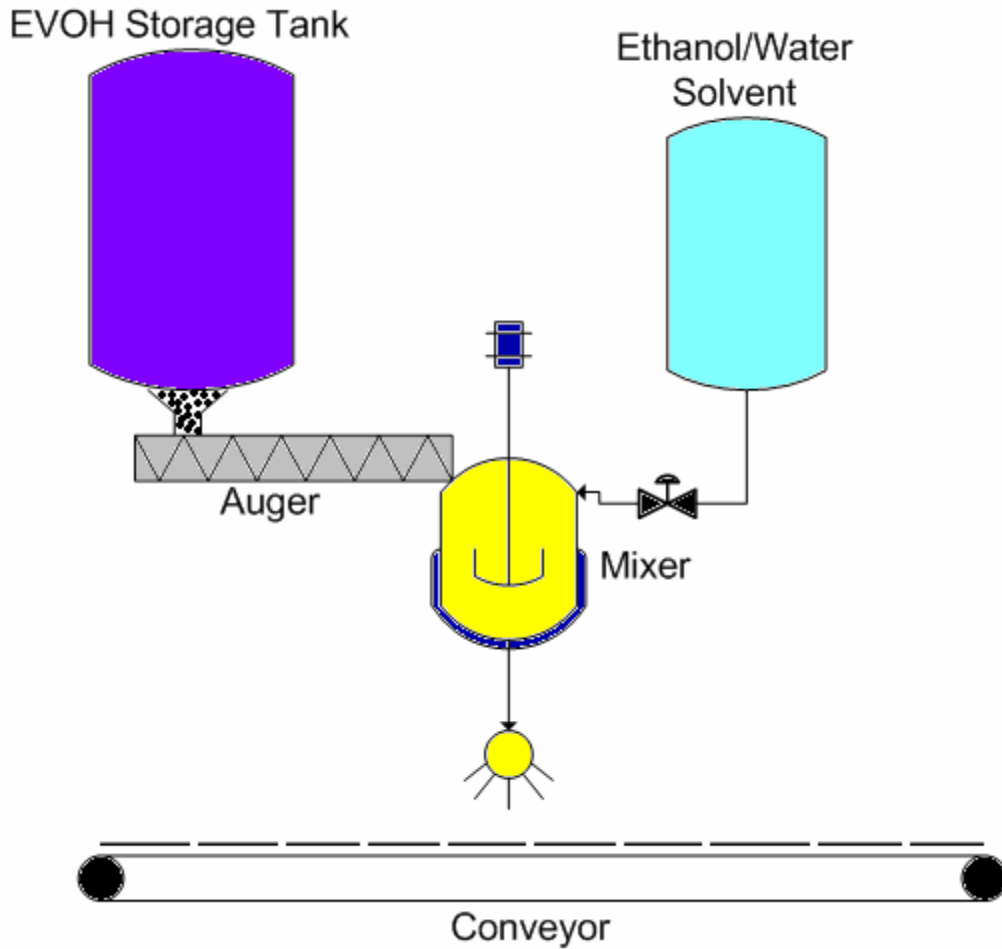


FIGURE 34: EVOH spraying section.

The EVOH/solvent solution is sprayed on the Curv® sheets using maleic anhydride as an adhesive. After the tank halves are stamped and connected, the seam must also be sprayed so gas cannot diffuse through the seam. The solvent evaporates from the mixture after application.

After the tank halves have been stamped, they must be joined together. During stamping, flanges will be formed on each of the tank halves. These flanges will be heated and pressed together. Steel rivets will then be punched through the flanges to secure the halves together. The steel rivets will be placed 3 inches apart along the sides of the tank and 3.2 in. apart on the ends.

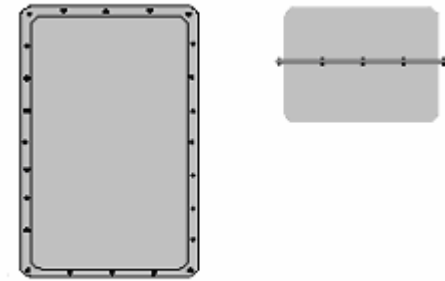


Figure 35: Rivet placement.

Risk and Uncertainty Analysis

Handling the risk and uncertainty for this project was a difficult task. There was no way to assume how many contracts we would be able to secure before actually talking to automobile manufacturers. In order to handle this problem, we used the program evaluation and review technique (PERT) diagram shown below in FIGURE 36.

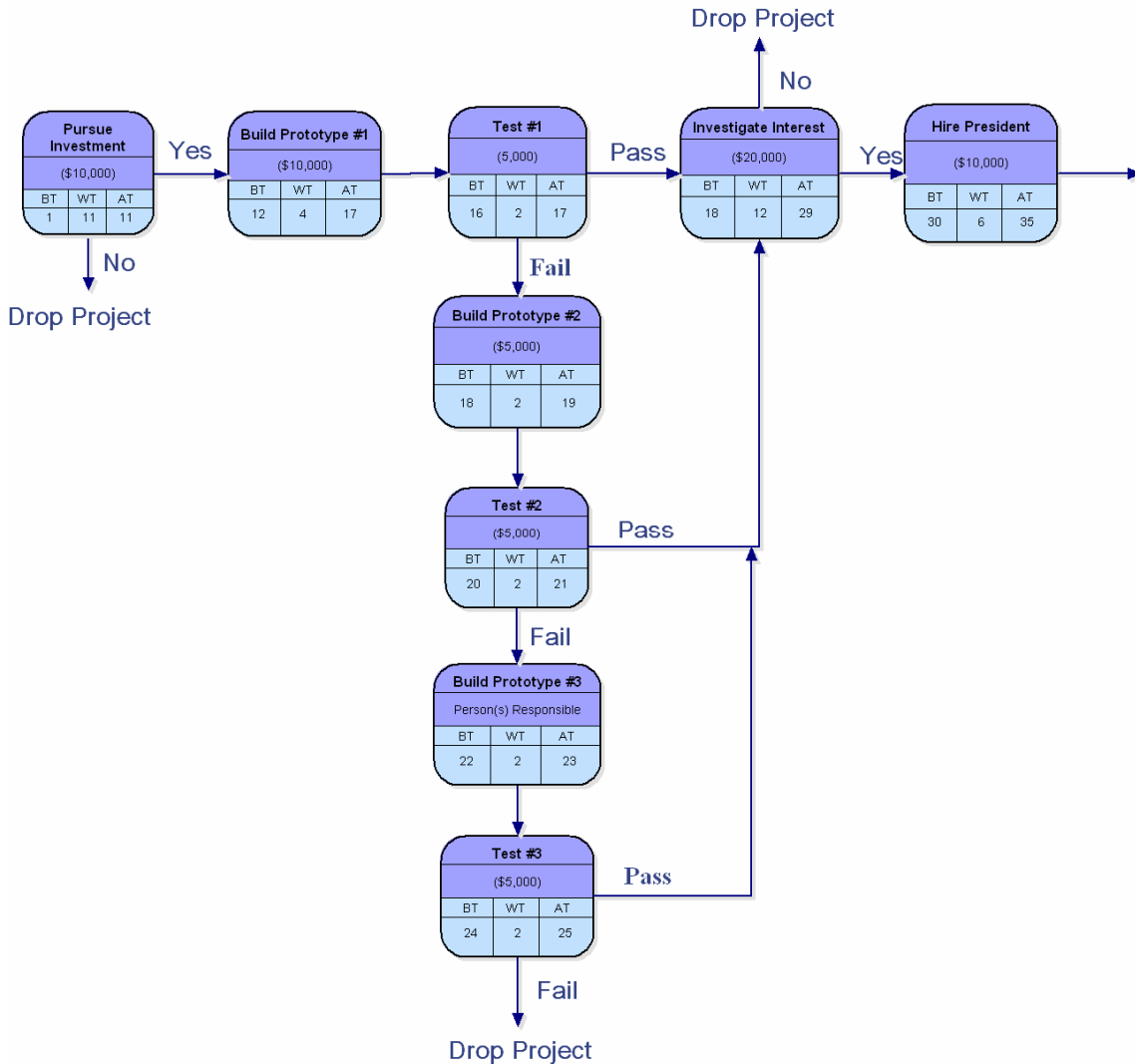


FIGURE 36: First half of Pert diagram.

At the start of the project, a private party will use their own money to pursue an investor(s). If no investor can be found then the project will be dropped. Upon getting an investor to back the venture, several prototypes will be built to show to the automobile manufacturers during the stage of investigating interest in our new product. The first prototype will be impact and emissions tested. If it fails either of the tests, then another prototype will be built and tested. In the occurrence that a third prototype has to be built and still does not pass, the project will be dropped. The chances are small that more than one prototype will have to be built, because the theory behind the design is sound. After developing a successful prototype, General Motors, Nissan, and Honda will be approached to investigate their interest in using our polymer composite tank. If these

companies are interested in using our product, then we will move on and hire a president. Once the president has been hired we will proceed to the second phase of the PERT diagram shown below in FIGURE 37.

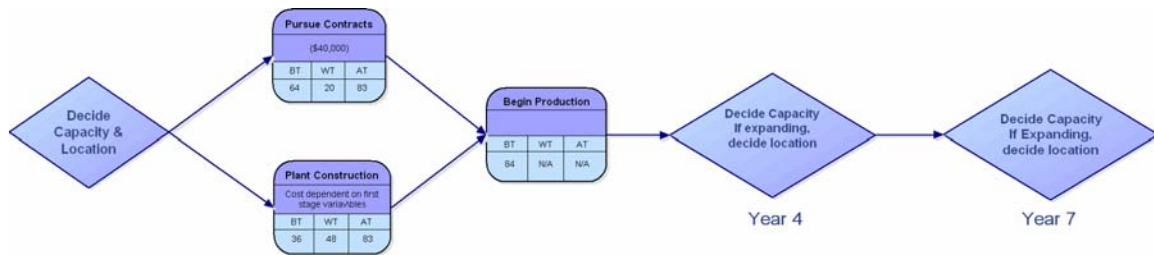


FIGURE 37: Second half of Pert diagram.

Based on the level of interest, plant capacity and location will be decided upon. After making these two decisions, plant construction will begin. Midway through the plant construction the interested companies will be approached in order to pursue contracts. Production will begin as soon as the plant construction is finished. In the case that the plant is finished before any contracts go into effect plant construction will begin. In the fourth year the operating capacity will be re-evaluated. If it is desirable to expand, the size and location of the expansion will be determined based upon the contracts. This evaluation will be carried out again in year seven. Usually a plant will evaluate the need to expand every two years. However, our project only has a life time of ten years, so we chose to only look at the need for expansion every three years. The reason that the project life is limited to only ten years stems from the nature of the market. The development of plastics is continually advancing. New products come into the market all the time, and one of these products may make our design uneconomical. Steel tanks are also on a slight comeback due to the development of a new coating that decreases emissions.⁵⁵ Due to these and other issues the project lifetime was limited to ten years. The plant construction node in the above diagram expands into the diagram shown below in FIGURE 38 and 39. During this time the equipment will be purchased and installed, the plant personnel will be hired and trained, and the raw materials will be purchased.

⁵⁵ *CSM Insights*, "Steel Tanks: Can they Make a Comeback?", Summer 2002

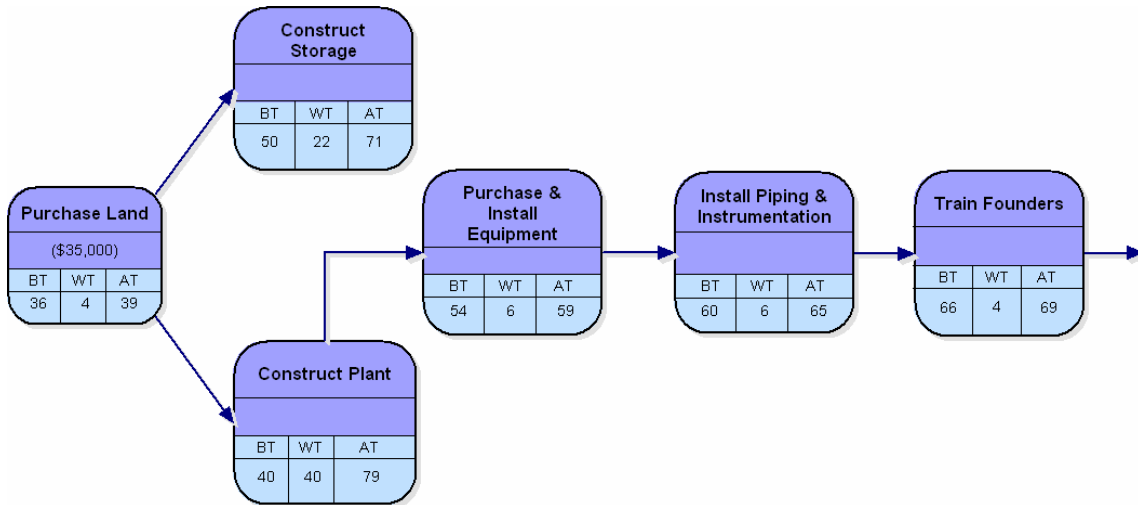


FIGURE 38: Plant construction.

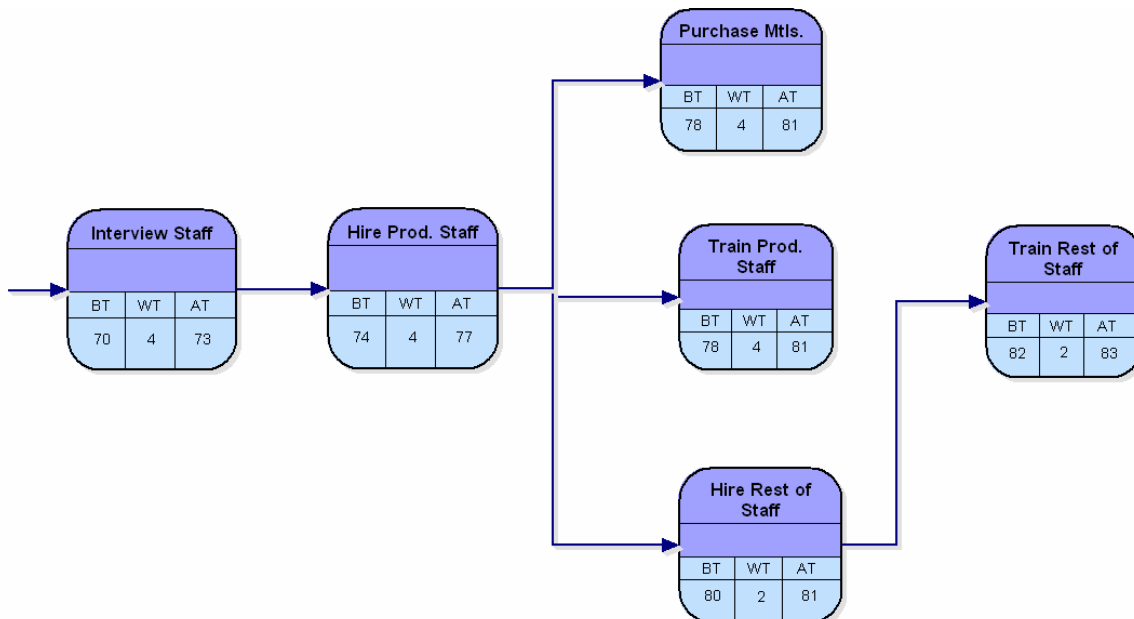


FIGURE 39: Plant construction continued.

With this developed model, risk and uncertainty can be evaluated. The two important nodes in the PERT diagram are the investigating interest node and the pursuing contracts node. Twenty-seven different models were considered for this project (see TABLE 14 below).

Table 14: Different models considered for this project

Nissan	Production (units/yr)	Tank Size (gal)
Altima	201,240	20.0
Maxima	86,758	20.0
350Z	36,728	20.0

G35 Sedan	35,765	20.0
G35 Coupe	28,965	20.0
Honda		
Civic	305,000	13.2
Accord	393,300	17.1
TSX	17,000	17.1
TL	50,000	17.1
RSX	26,250	13.2
General Motors		
Impala	267,800	17.0
Monte Carlo	156,500	17.0
Century	184,300	17.0
Regal	64,700	17.0
Grand Prix	150,000	17.0
Malibu (& Malibu Maxx)	200,000	16.0
Le Sabre	64,700	18.0
Park Avenue	23,500	18.0
Bonneville	21,800	18.0
Cavalier	182,300	14.0
Sunfire	57,600	14.0
Grand Am	115,500	14.0
Ion	86,100	13.5
Saturn L Series	79,800	15.7

TABLE 14: Different models considered.

The possible levels of interest received from a company were assigned to be high, medium, or low. The level of each interest was determined by examining the production numbers of the model, the importance of the model to the company, and the prestige level of the model. For instance, a model with high production numbers generally has a medium or low interest level because a manufacturing company would not want to risk a recall on the model if the new project should have a problem. The automobile manufacturers would be more likely to give a smaller contract initially and increase the number of tanks purchased later. A car with high prestige (luxury, sports, executive, etc.) was given a lower rating, because manufacturers are not likely to take a chance on their nicer model since they want to have clean reputations to attract repeat customers. The Honda Accord is not a high prestige car, but it is undoubtedly one of Honda's flagship models and they would not be likely to take a chance on a new product in such a model. In essence, the higher probabilities for contracts will more than likely be for the lower and mid-range models with moderate production numbers. Using this logic, probabilities for getting an interest level of high, medium, or low were determined for each model

considered. Eight models were chosen that all shared a common fuel tank capacity to make the problem more manageable. The eight models considered are shown below in TABLE 15 with their respective probabilities.

Model	Production (units/yr)	High	Medium	Low
Impala (GM)	267,800	P=0.2	P=0.6	P=0.2
Century (GM)	184,300	P=0.2	P=0.5	P=0.3
Monte Carlo (GM)	156,500	P=0.15	P=0.45	P=0.4
Regal (GM)	64,700	P=0.2	P=0.5	P=0.3
Grand Prix (GM)	150,000	P=0.1	P=0.4	P=0.5
TSX (Honda)	17,000	P=0.35	P=0.5	P=0.15
TL (Honda)	50,000	P=0.25	P=0.5	P=0.25
Accord (Honda)	393,300	P=0.1	P=0.4	P=0.5

TABLE 15: Interest level probabilities for considered models.

The next node of importance is the pursuing contracts node. For an interest level of high, the probability of actually getting the contract is assigned to be 80%. An interest level of medium results in a 50% chance of getting the contract and an interest level of low results in a 20% chance of getting the contract. The system is now set up for risk analysis. To analyze the data numbers of 1, 2, or 3 (1=high, 2=med, 3=low) were generated for each model's interest level. The number of times a particular interest level was generated corresponded to its' previously assigned probability (i.e. \approx 20% of Impala interests were 1). These outcomes were first stage variables. One thousand outcomes were generated. As stated before the plant capacity is based on the outcome of the interest levels selected. The planned capacity of the plant was determined by summing the production numbers of all models whose interest level for that particular outcome was a 1 or a 2. Using the financial evaluation sheets, relationships were developed for the total capital investment (TCI), fixed operating costs (FOC), and variable operating costs (VOC) as a function of capacity. The expected capacity of the plant was the sum of each model's production multiplied by the probability of obtaining a contract based on its particular interest. The expected revenue was calculated using the expected capacity, not the total capacity. The TCI and the FOC were calculated for each outcome based on the total capacity, and the VOC was calculated based on the expected capacity. Profit for each outcome was calculated by subtracting the FOC and VOC from the revenue. The net present value of

each outcome was calculated for a ten year project life using an interest rate of 3.69%⁵⁶ a constant cash flow for all ten years equal to the profit, and the TCI. Because such a large number of outcomes were generated, each was assumed to have the same probability. Using these probabilities the risk (cumulative probability) was calculated for each NPV. Using this information a risk curve was generated. As you can see from FIGURE 40 below, the project only has a 9% chance of losing money. The value at risk was found to be \$20.4 million and the opportunity value was found to be \$31.8 million. This investment is not too risky. An investor should find this to be satisfactory. The standard deviations in the raw material prices were evaluated using Crystal Ball (Excel based program for evaluating uncertainty). They did not significantly affect the NPV's, so individual price scenarios were not considered for each outcome.

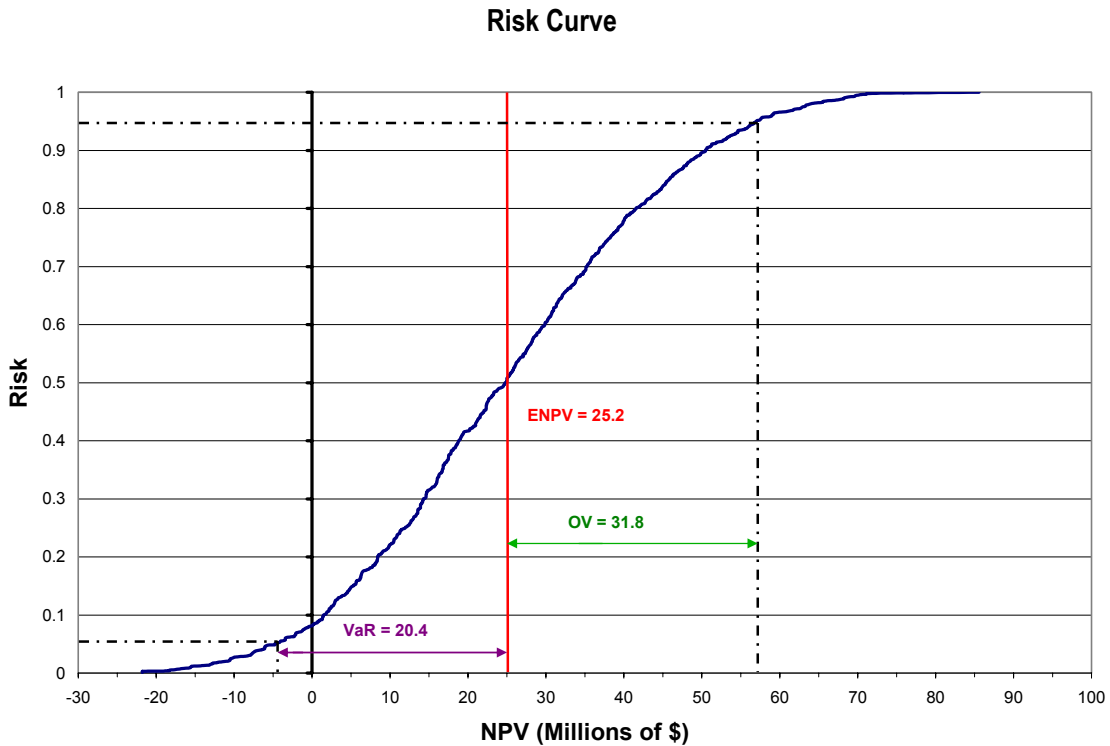


FIGURE 40: Risk curve.

⁵⁶ <http://www.forecasts.org/interest-rate/10-year-treasury-bond-yield.htm>

Uncertainty Analysis Recommendations

The situation of acquiring contracts and planning the number of contracts you will obtain is very interesting. It would be beneficial to develop a linear programming model to evaluate this problem. A deterministic model could be developed to make the best decisions taking into account the important parameters simultaneously. Major factors affecting the operating costs were the wages and the transportation costs. This shows that location is very important for this project. The developed model should generate outcomes of interest level based on the probabilities assigned to each level of interest. This could be done using the same logic used for this project. Once an outcome was generated, the interests received could be used to determine location based upon the transportation costs and labor rates. After determining the best location, the program would fix plant location and capacity and then run several hundred scenarios on each outcome by varying the prices of the raw materials and the selling price of the tank. For each outcome the expected net present value could be calculated. After all the outcomes were generated and the scenarios were also completed, risk could be evaluated. A risk curve could be generated for each outcome, and an overall risk curve could be generated considering all the outcomes. It would be necessary to input a list of possible plant locations, car models being considered with production numbers and locations of the plants at which they are assembled, transportation costs, location specific costs (tax rates, energy costs, labor rates, etc...), distances between possible plant locations and the locations of the assembly plants, prices of all materials including their standard deviations, equipment costs, and any other parameters that might be influential. Expansion considerations will need to be added to the financial model to determine if and when the company will expand. This method is definitely more complex, but it would be more accurate than the method used.

Future Considerations

Gauging the market interest is the most important area that can be improved upon. Direct contact with the automobile maker is the most effective way to gauge interest in the market. Our financial model would need to be modified to include extensive

traveling to manufacturing headquarters, company headquarters, automobile shows, aftermarket parts shows and other related expenses to support this.

From this increased contact with the automobile manufacturers, new models will need to be evaluated and considered for polymer gas tank fitting. The possibility of overseas sales will also further complicate tank design because other countries may have different laws and regulations controlling emissions. Patent lawyers will need to be hired to protect design specifications if the tanks will be in countries other than the United States.

Appendix

Economic Sample Calculations

Return on Investment (ROI)

$$\text{ROI} = (\text{Average annual net profit})/\text{TCI}$$

For Cincinnati, 500k tanks, \$50/tank:

$$\text{ROI} = \$8.45\text{mil}/\$2.99\text{mil} = 283\% \text{ annually}$$

Payback Period

$$P = \text{FCI}/(\text{Average annual net profit})$$

For Cincinnati, 500k tanks, \$50/tank:

$$P = \$2.53\text{mil}/\$8.45\text{mil} = 0.3 \text{ years}$$

Net Present Worth (NPW)

$$NPW = \sum_{\text{year}}[(\text{present worth factor}) * (\text{annual cash flow})]$$

For Cincinnati, 500k tanks, \$50/tank:

$$\begin{aligned} NPW = & (0 * \$1.63\text{mil}) + (1.42 * \$-0.38\text{mil}) + (1.23 * \$-0.89\text{mil}) + (1.07 * \$-1.72\text{mil}) + \\ & (0.93 * \$4.28\text{mil}) + (0.81 * \$7.77\text{mil}) + (0.71 * \$9.34\text{mil}) + (0.61 * \$10.26\text{mil}) + \\ & (0.53 * \$9.96\text{mil}) + (0.46 * \$9.63\text{mil}) + (0.40 * \$9.30\text{mil}) + (0.35 * \$9.02\text{mil}) + \\ & (0.31 * \$8.75\text{mil}) + (0.27 * \$8.28\text{mil}) = \$41.4\text{mil} \end{aligned}$$

Location Specific Labor Cost

$$\text{Location Specific Labor Cost} = (\text{average location labor cost}) * (\text{location specific labor index}) / (\text{average labor index})$$

For Cincinnati, 500k tanks, \$50/tank:

$$LSLC = \$0.973\text{mil} * (13395 / 14566) = \$12.3\text{mil}$$

Flexural Strength Sample Calculation

$$S = \frac{3PL}{2bd^2}$$

where S is the stress in outer fiber at midspan, P is the load at a given point, L is the support span, b is the width of the beam, and d is the thickness of the beam. Rearranging and solving for the maximum load, the equation becomes:

$$P = \frac{2Sbd^2}{3L}$$

Using high density polyethylene as an example, and using the gas tank dimensions that were used for financial evaluation(0.4064m x 0.625m), the maximum load that may be endured can be calculated below.

$$P = \frac{2(25MPa)(0.4064m)(0.00241m)^2}{3(0.625m)}$$

$$P = 63.1N$$

Diffusion Calculations:

The following picture will be used as reference to the calculations done below.

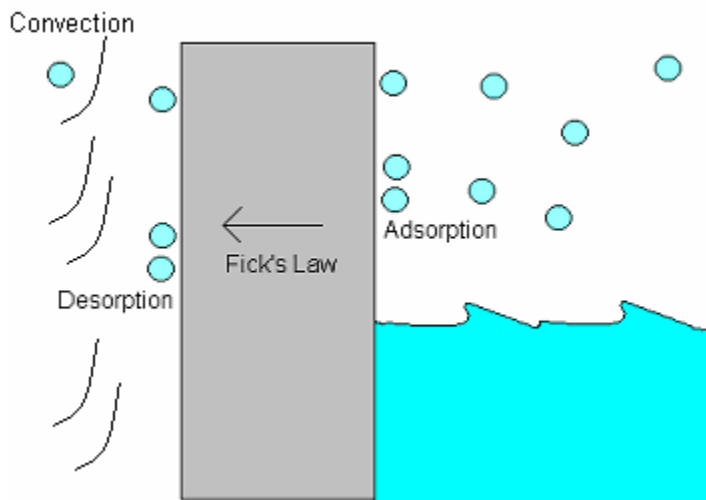


FIGURE 41: Diffusion.

Fick's Law : $J = D_{ab} \times \frac{dc_a}{dz}$

Situation: One dimensional, steady state diffusion through barrier. Integrating Fick's Law yields:

$$N_a = \frac{D_{ab} \times (c_1 - c_2) \times A_s}{l}$$

By incorporating Henry's Law ($C = S \times p$) and the definition of permeability ($P = S \times D_{ab}$) the following equation can be derived:

$$J = \frac{P \times A \times (p_2 - p_1)}{l}$$

where $J = \text{mol/s out}$

P= permeability
 A= surface area
 p= partial pressure
 l= length

Convective Mass Transfer- Ref Fuel C into Air

$$k_c = \frac{D_{ab}}{x} \times (0.332 \times Gr_x^{0.5} \times Sc^{1/3})$$

where k_c = convective mass transfer coefficient
 D_{ab} = diffusion coefficient
 x = local length
 Gr = Grashof number
 Sc = Schmidt Number

Solving for k_c

$$k_c = \frac{5.79 \times 10^{-6} \frac{m^2}{s}}{0.24m} \times (0.332 \times (4.58 \times 10^{-8})^{0.5} \times (2.708)^{1/3}) = 2.39 \times 10^{-9} \frac{m}{s}$$

Entering this expression into the mass balance equation:

$$k_c \cdot A_x \cdot (C_{a_s} - C_{a_\infty}) = W_a$$

$$3.163 \times 10^{-9} \frac{mol}{s} = 2.39 \times 10^{-9} \frac{m}{s} \times 1.0282m^2 \times C_{a_s}$$

$$C_{a_s} = 1.282 \times 10^{-6} \frac{mol}{s}$$

Because the flux out of the mass balance equation was set equal to that of the EPA emissions limit, the concentration solved for above represents the maximum concentration that can be present at the boundary layer between the barrier and the atmosphere after it has desorbed from the barrier. To check for this limit, Fick's Law needs to be solved for c_2 and compared. However, as stated in the report, the solubility coefficients are unknown and permeabilities are only known. For this reason it is assumed that instead we are in a worst case scenario which makes more sense from a design prospective. In a worst case scenario there is no boundary layer to provide resistance so it can be assumed to be zero and the total flux out is calculated solely from Fick's Law.

To solve for thickness using EVAL permeabilities the following equation needs to be used:

$$Thickness = \frac{Permeation \times Area}{Diffusion}$$

The F-series is the automobile manufacturers standard so it will be used:

$$Thickness = \frac{0.0009 \frac{g-mm}{100in^2-24hr} \times 15.93in^2}{0.35g} = 0.40microns$$