Economic Evaluation of Automotive Shredder Residue Disposal Options

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Abstract

In this project an economic evaluation of ASR (Automotive Shredder Residue) disposal options was performed. The methods identified and analyzed included landfilling ASR, ASR recycling, ASR incineration, ASR pyrolysis, and design of automobiles for disassembly. It was found that alternative methods to landfilling could be more profitable, however, many of the industries have not been widely developed. The best option for the disposal for ELV's (End of Life Vehicles) depends on the capital available for investment and costs of disposal that vary with location due to available space for landfilling and legislation of emissions. It was found that total disassembly on a large scale is the most profitable and environmentally friendly option. However, the common practice of landfilling ASR is resistant to change and total disassembly is not widely practiced.

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1.0 Introduction

The evolution of the automobile has given rise to vehicles that run longer, are more fuel efficient, safer, and cost less to produce. These advances may be attributed to improvements in engineering technology and the expanded variety of materials available for production. While materials used for the moving parts of automobiles such as the engine and transmission have remained relatively unchanged, using mainly steel and aluminum for their fabrication, plastics have found increased usage in other areas of automobile manufacturing. While the implementation of plastics in automobiles has improved the corrosion resistance properties and decreased the total weight of the automobile, the effects of their increased usage may not be beneficial for the environment [1].

Production of lighter vehicles has led to an increase in the variety of materials used. Weight reduction is a common goal in the auto industry to increase the fuel efficiency. Since 1975, the average weight of an automobile has dropped from 4000lbs to 3300lbs [2]. Of this weight, 2250lbs are recycled, with the majority of this recycled material consisting of steel, aluminum, copper, and zinc. Future goals set by *The Partnership for a New Generation of Vehicles* (PNGV), which includes all major automobile manufacturing companies, include achieving an average gas mileage rating of 80mpg and a vehicle body weight of 2000lbs [2]. With this goal in mind, it has been concluded that the future use of alternative lightweight materials for the body and internal structural support will be increased [3]. By cutting back on steel use, the total automobile weight will be drastically reduced. However, the increased use of other materials to replace steels, primarily plastics, will increase the technology required to recycle the material.

One method of making materials more environmentally friendly is to manufacture materials that are more easily recyclable. When the term “recycle” is used, most people think of newspapers, aluminum cans, and glass bottles at the town-recycling center, yet the most recycled product in the world is actually the passenger automobile. Of the 10 million vehicles disposed of each year, 95% are at least partially recycled. By weight, 75% of the vehicle is recycled, the majority of which is metal. The remaining 25% is referred to as automobile shredder residue (ASR). Of the ASR, 40% is plastic and the other 60% consists of textiles, glass, and rubber [4]. While the plastics can be separated from these other materials present in ASR, the plastics present a challenge to recycle since many plastic types have differing chemical compositions and cannot be processed together [5]. As a consequence, ASR is sent to landfills instead of being separated and recycled. Currently the methods available to separate these various plastics are not economical; therefore, ASR is expected to continue to be landfilled until an economic alternative for recycling is available [4]. The future of the automobile industry is headed towards the cost-effective production of lightweight automobiles, and as a result increased concerns exist that larger amounts of ASR will be generated and find its way to landfills [6].

Although these statistics appear to suggest that recycling in the automotive industry is largely successful, there is concern that the percentage of recycled parts may decrease if the movement to produce lighter weight vehicles continues [1]. Although plastics are not currently recycled in the automotive industry, this problem is not likely to be a deciding factor for future engineers when making decisions to use the least expensive light weight material when designing a vehicle. Currently, the material cost for steel is about half the price of other automotive materials available, with plastic, aluminum, and other exotic materials costing more money in comparison. The low tooling cost for the shaping of plastic parts compared to steel has kept plastics competitive for some applications [12].

The goal of this project was to determine which disposal methods currently available or under development could be made economically beneficial to encourage the reuse of plastics from automobiles. Since there is a growing trend toward the use of lightweight materials in vehicles, the use of plastics in automobiles will increase, and more plastics will be sent to landfills unless a method for recycling them can be made to be profitable. A cost analysis of the different disposal methods of automobile plastics was performed.

Four approaches that were examined were:

1) Sending the automotive plastics to landfills
2) Recycling of ASR
3) Energy recovery by incineration or pyrolysis
4) Design for the disassembly of end of life vehicles to recycle plastic parts for reuse before ASR is generated.

Through the use of interviews with people involved in the automotive, plastic recycling, and other related industries, disposal of automobile plastics were compared economically to find a cost-effective solution to the problem.

2.0 Background

Background research was necessary to be able to economically evaluate disposal options for automotive plastics. It was important to learn what types of plastics are used in automobiles, why plastics are used, and the methods used to manufacture them. The background research for this project consisted of a literature review of books, journals, and magazines related to the topic. Since much of the technology in this field is very recent, the much information from the Internet and World Wide Web was used, by performing a search on the related topics. Research was also performed on current techniques of recycling and disposal options by interviewing people working at companies related to this project.

2.1 Automotive Recycling History

Recycling of the automobile has occurred since its development; however, it was not until the 1960's that it became a national interest. Car disposal made it to the national agenda when abandoned cars began to pile up along highways and in junkyards. Legislation was proposed to deal with the increasing problem; however, it was a technological innovation that resolved the crisis. This innovation was the automotive metal shredder [24].

Up until the 1960's, automobiles were partially recycled, in a similar fashion to what occurs at a salvage yard. Between the 1940's and 1950's a common practice was to remove the valuable parts from an automobile and then set the remaining automobile on fire to remove the less valuable combustible materials so the remaining metal could be recycled. Cutting torches were then used to separate and remove the metal parts. The metals were separated by type, and the most valuable was steel, which could be easily recycled in an open-hearth steel furnace, which was commonplace during that period [24].

In the 1960's steel making took a turn, with the basic oxygen furnace replacing the open-hearth steel furnace. While this was an improvement from the point of view of the steel manufacturers, it decreased the types of steels that could be recycled. Now only 28% of the scrapped steel could be recycled, versus 45% previously. This decrease in steel recycling caused many automotive salvage yards to go out of business, which led to the abandonment of these automobiles on the side of roads and abandoned fields [24].

After the 1960's the electric arc furnace became the new standard that quickly swept through the steel making industry [24]. This allowed for nearly 100% of all scrapped steel, including automobiles, to be recycled. Not long after this innovation, metal shredders were developed in conjunction with crushing devices and ferrous metals separators, allowing automobiles to be economically recycled. Automotive Shredder Residue (ASR) is the lightweight "fluff" generated during the shredding and metal recovery stages of automobile recycling. Practically overnight the abandonment of automobiles disappeared, and the new industry of automobile shredding emerged [24].

2.1 Plastics in Automobile Panels

Plastics are comprised of long chains of molecules called polymers. These polymers are formed by reactions where large numbers of monomer molecules react with each other to form long chained molecules. These molecules often can have molecular weights in the tens of thousands or higher. Since plastics are comprised of small atoms such as hydrogen, carbon, oxygen, and nitrogen, which leads to the relatively low density of plastics. Plastics can be easily molded and extruded [11].

The polymers that form plastics can be divided into two classes, thermoplastics and thermosets. Thermoplastics are easily softened by heat, and can then be reformed into another shape, allowing thermoplastics to be much more easily recycled. Thermosetting polymers are not softened by heat, and cannot be reshaped, due to the extensive crosslinked network of thermoset plastics [12], making them more difficult to recycle. Some types of plastic are made from more than one type of polymer resin and are called co-polymers. These are more difficult to recycle than polymers made from one type of resin called homopolymers because a high degree of purity of a polymer type is sometimes required.

A wide variety of polymers can be used for automotive parts materials, including both thermoset and thermoplastic polymers. Thermoplastics that are commonly used include polymer blends such as polyphenylene ether/polyamide (PA), ABS/PA, polycarbonate/ABS, and amorphous polyamides. A study was performed on alloys of polyphenylene ether/polyamide, ABS/polyamide, ABS/polycarbonate, and ABS/polyester. It was found that these polymers had temperature resistances up to 117-121°C, with enough strength to be used in vertical panels and sufficient impact resistance [7]. Thermosets that are commonly used include SMC (Sheet Molding Compound), polyurethane RIM (Reaction Injection Molding) and polyurea RIM.

A car may be manufactured with an all-plastic body, or plastic with some parts replaced by metal parts. For the metal replacement case, the plastic parts may be painted "online" with the rest of the vehicle or "offline" if they are painted separately. Online

VRDC U.S. Field Trial

1988-1994

Tempo & Topaz

Summary of Weights and Times

Material	***Total Contaminated Weight (lbs) ****	***Total Clean Weight (lbs) ****	***Total Removal Time (min) ****	***Total Cleaning Time (min) ****	***Total Time (min) ****
PP	42.70	22.86	13.07	9.20	22.27
EPDM	15.60	15.60	0.72	0.00	0.72
Aluminum	19.22	14.94	3.58	5.92	9.50
ABS	9.38	7.95	4.92	1.55	6.47
TEO	3.21	3.13	2.65	1.00	3.65
PA66	1.79	1.54	0.37	0.17	0.54
	91.90 lbs	66.02 lbs	25.31 min	17.84 min	43.15 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time

*These totals do not include the Depollution data

painting is more difficult to incorporate, but allows for better color matching and easier assembly line production [7].

The relatively low tooling cost (cost to shape the material) of plastics compared to steel helps offset the higher material cost of plastics, especially at low production volumes. If oven and assembly line temperatures can be reduced, less expensive thermoplastic alloys may be used that are competitive with steel [7]; however, reduction in steel tooling costs will reduce competitiveness of thermoplastics. Low tooling costs allow for easy changing to update style changes and alterations while using a standard vehicle assembly platform.

It may be difficult for suppliers to change from steel to plastic automotive parts unless the manufacturer possesses the technology to use them. Collaboration between the auto manufacturer and suppliers may lead to the use of a greater variety of materials [12]. Currently, capital equipment in the manufacturing industry is centered around the use of steel. Increasing the number of different models available by auto manufacturers and decreasing the number of vehicles of each model may eventually lead to the use of more plastics [12].

Compression molded SMC has been used in the Chevrolet Corvette and the Pontiac Fiero due to its high temperature resistance, which allows it to be painted in the same manner as steel autos, and manufacturing has allowed technology for competitive build rates. Reaction injection molded polyurethanes and injection molded thermoplastics are used in some auto parts applications, such as bumpers [12].

A thermoplastic polymer combined with 30-40% fiberglass has produced a new material for auto bodies. Advantages include the ability for high production rates, no hot molds since the material can be pre-heated and compression molded, and greater recyclability than thermosets [8].

It has been noted that painting of plastics may weaken the impact strength. A crack that originates in the outer paint layer propagates downward creating a stress concentration on the plastic, lessening the impact resistance [10]. For plastics to become prominent, methods must be found for parts consolidation, reduced life cycle and insurance costs, and reduced capital and overhead costs for auto makers [12].

2.2 Used Plastic Material Collection

Good citizenship has been the main focus in attempts to persuade individuals to recycle; however, it is well known that economic factors are much more important for recycling to take place on a large scale. Without a continuous supply of used plastic as the starting resource, recycling can not occur. That is why it is important to realize that used plastic material collection is the starting point in the recycling loop, and without well developed methods to initiate this used plastic collection, recycling could never occur. Common methods used to increase collection of used plastics include redemption incentives, legislation, and community collection programs [17].

2.2.1 Redemption Incentives

Redemption incentives for selected used plastic containers have contributed to the increase in amount of plastic recycled each year in the U.S. Prior to 1989, very few beverage companies offered a monetary incentive for the recycling of their plastic bottles. However, by 1994 most beverage companies that distributed plastic bottles offered a preset monetary amount for the return of their bottles. This monetary incentive resulted in an increase of over 300,000 tons of recycled plastic per year. Compared to 1989, when only 100,000 tons were recycled annually, this monetary incentive boosted recycling by 75% [18]. Despite this increase, the total plastic recycled remained low at a recovery rate of only 4% [18]. This is attributed to the fact bottles comprised only a small fraction of the total amount of plastic products

2.2.2 Legislation

Specific forms of legislation have been suggested here in the US which would require automobile manufactures to take back their products at the end of their service life [18]. In essence, this type of legislation would theoretically force automobile manufactures to develop methods in which the vehicle would be recycled entirely. This type of legislation was proposed in Germany in 1994 but did not pass [17]. It has made manufacturers aware of the concern and consequently, on a voluntary basis the German automotive industry organized a network of licensed automobile dissemblers, which return all vehicle components to the appropriate raw material producers. In the first 8 months VW's disassembly facility removed over 50,000 plastic bumper fascias and recycled them into fascias for new cars [17]. Had this legislation not been proposed, those fascias would have been converted to plastic shredder residue and sent to landfills.

2.2.3 Community Collection

Collection of plastic materials by communities has recently become an added pipeline to the overall collection effort. Community collection is based on the overall costs to the community, and the income from the sale of virgin material. The costs to the community include: 1) the cost to collect the recyclables; 2) cost to sort the recyclables; 3) cost of trash collection; and 4) cost for landfill usage [17]. Since the price of virgin material for plastics is directly related to the price of oil, community collection of plastics becomes non-profitable when crude oil prices are low. This assumes that costs for landfill usage are low and the added effort to collect and sort the recyclable plastic is high. Based on an average landfill cost of $75 per ton of waste, and ignoring the collection and sorting costs, Figures 9 and 10 show the economic impact a change in crude oil prices have on community recycling.

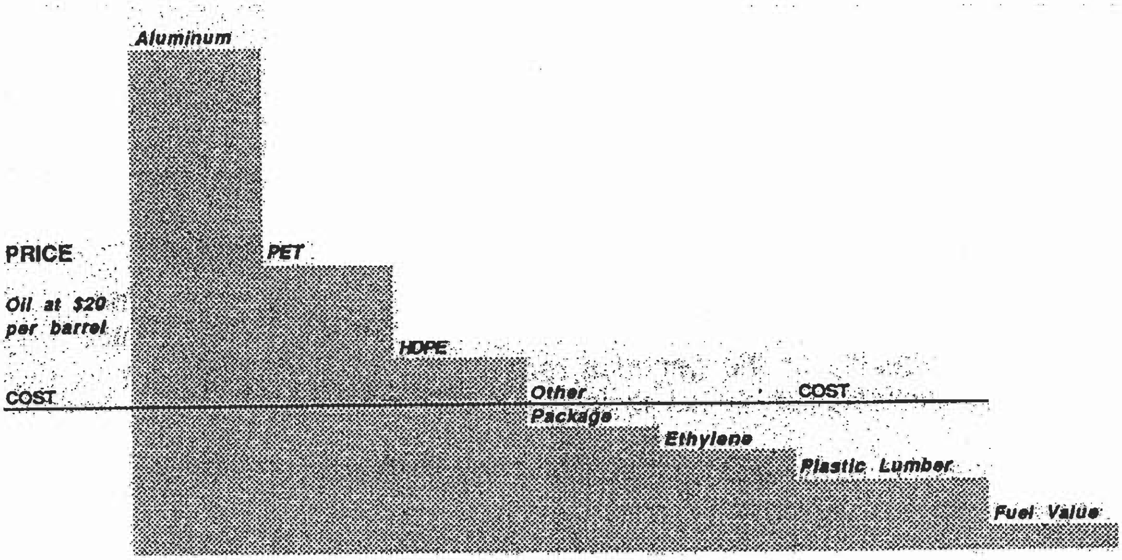


Figure 9. Viability of Plastics Packaging Recycling vs. Today's Virgin Prices Based on Oil at $20/Barrel.

Source: Andrews [17]

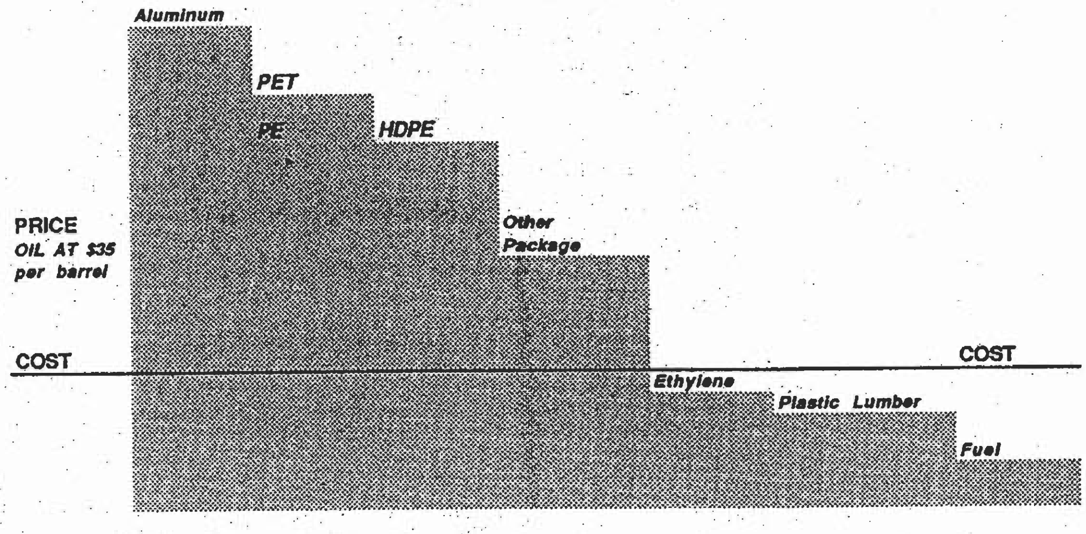


Figure 10. Viability of Plastics Package Recycling vs. Virgin Prices Based on Oil at $35/barrel.

Source: Andrews [17]

At $20 a barrel, PET and HDPE are the only plastics that are economically recyclable; however, at $35 a barrel, profitability of recycling PET and HDPE increase dramatically, while other plastic types become economically profitable to recycle as well. Stockpiling plastics drives the continuation of plastic collection in times of low crude oil prices since there is a "future value" for plastic material [17].

2.3 Plastic Separation Techniques

After collection of used plastics, the second step in plastic recycling is the separation process. This step is crucial in the recycling process of plastics, and dictates a large percentage of the final recycling costs as well as the purity of the outgoing plastic streams. Plastics that are recycled can be classified ultimately into two categories: 1) commingled, or 2) separated. Separated plastics are those which are pure upon being separated and are most valuable. Commingled are those that cannot be totally separated, causing a change in physical characteristics from the original product [17]. Ideally, it is desired to find a separation process that would yield a near perfect separation of all plastics at a low price. Unfortunately, however, no perfect method exists yet to do that. The following sections below describe the separation methods currently available.

2.3.1 Density Separation

This technique involves the use of a liquid to separate chopped plastic particles from other undesirable particle types. Under typical circumstances this process is not highly selective in separating different plastic types from one another, and is mainly used to remove other materials (glass, metals, etc.) from the plastic feed stream. Recently, however, new techniques involving the use of supercritical fluids have been developed so that the separation of various plastics with similar densities can be achieved to a high degree of purity [17]. Simply varying the temperature and/or pressure of the supercritical fluid changes its density, allowing multiple separations of varying plastic types to occur. Attempting to do a multiple plastic separation using conventional methods requires the use of many liquid types in series. This process is lengthy, and normally not cost effective since the plastics typically require cleaning between liquid separations. In addition, the liquids used are commonly toxic and special precautions must be taken. The supercritical fluid method appears to be a viable replacement technology since it uses a non-toxic CO_2 and SF_6 mixture as the fluid, and can do multiple plastic type separation without the requirement of using multiple liquids. The only drawback appears to be the specialized equipment required to provide the environment necessary for the formation of the super critical fluid. Since this technology is new, the initial cost of that equipment is expected to be high [17].

2.3.2 Electrostatic Separation

Electrostatic separation requires the plastic material to be chopped into particle sizes ranging from 150-mesh to 0.5 inches. Once chopped, the feed stream is transported through an apparatus, which contains multiple electrodes that induce an electric field onto the plastics and non-plastic species present. Typically, this process cannot separate multiple plastic types from one another, and so is mainly used to remove other non-wanted components such as metal [18].

2.3.3 Molecular Separation

Molecular separation involves the separation of plastics on the molecular level by dissolving the plastic in an organic solvent. Condensation polymers are among the easiest to separate in this fashion [17]. In most cases where molecular separation can be applied, a high amount of separation can be obtained. This type of separation is commonly used for PET in the recycling process of soda bottles. PET isn't the only plastic that can be separated in this fashion; in fact, demonstrations have shown that by changing bath types and temperature ranges, up to five different plastics can be separated from each other using this method. The disadvantage to this process is that presently, in most cases, it is not cost efficient and the solvents required for the separation are environmentally dangerous. It is theorized that until either crude oil prices go up, or new cost-effective methods are developed, it will continue to be uneconomical to recycle most plastics using this method [17].

2.3.4 Spectrometer Separation

Spectrometer separation is a relatively new technology that has only recently emerged in the past few years. The technology, however, appears promising and possibly cost effective. It works by firing a laser that penetrates 100 microns into a plastic piece that only needs to be 0.5 mm in diameter [19]. The laser light causes the molecules of the plastic to vibrate. Certain photons within the spectrum of the laser light change frequency when they encounter the polymer chain, while others do not. Both photon types are reflected back to a detector which determines the "vibratory signature", which is unique to each polymer. This information is compared to stored material signatures in the computer database and a match is made. Originally, this system had a problem identifying materials containing carbon black; however, that obstacle has been overcome and the device can successfully distinguish ABS from PS as well as PPO, and can even detect PC coated with acrylic [19]. Another added bonus is that varying texture and dirt have no effect on the accurate detection of the material. Currently, there are two handheld models available from different companies, with price tags around $75,000. Both companies are developing automatic systems using this technology that will detect the chemical composition and try to separate plastics at a total mass rate expectancy of 49,000 kg a day [20].

2.4 End Uses of Recycled Plastics

Once separated, the plastic material is ready for reprocessing to be applied. Depending on the type of plastic being recycled, and the method used for its separation (purity level), the available options limit the final outcome of the recycled plastic material to one of the following final end applications. Reused plastic can be regenerated, used as new materials or fillers, or be used in a fuel feed stock.

2.4.1 Regenerated (Pure)

Separated thermoplastics have the highest value as a recyclable plastic type [17]. This is because regenerated plastics can be reused by blending them with virgin material and using it for their original purpose. Recycled thermoplastics are always blended with virgin material since bonds within the plastic's primary carbon-carbon chains may have been broken from overheating or light exposure during the lifetime use of the material. Simply melting these types of plastics back into liquids does not repair the broken bonds; however, blending with virgin material will produce a plastic product very close in quality to the virgin material alone [17]. Since thermoset plastics degrade before reaching their melting temperature, they cannot be reused as thermoplastics are by being blended with virgin material. Ford Motor Company's policy for the use of recycled plastics is, "It must perform as well as the virgin material for the part it is replacing, and the cost to manufacture the part must not exceed that of the virgin-material part [22]."

2.4.2 New Material (Filler)

Thermoplastics and thermosets can be used as a filler product for the production of a new material. This typically involves granulating or palletizing the used plastic material and physically blending it with new virgin plastic feed stock and/or other types of components [18]. The purpose of this is to minimize costs of the virgin material by reducing its total volume in the final product, by substituting it with the filler component. This recycling method is typically used for the production of outdoor fencing, benches, and picnic tables, as well as other non-critical type applications. Recently, this filling method using recycled plastics has also been applied successfully to asphalt and concrete volume enhancement [17].

In some cases, filler of a specific type is blended with another material, not to reduce cost, but to enhance the properties of the material to which it is being added. In this case, the final material is considered to be an engineered plastic and is referred to as an alloy [18]. In many cases, however, this filler material is not from recycled sources.

However, efforts are being made to use specifically selected recycled plastics for this purpose.

2.4.3 Fuel Feed Stock

Within the past three years an effort has been made by BP Chemicals to design a catalyst capable of being used for polymer cracking [21]. Much different from other form of polymer recycling, polymer cracking breaks apart the chemical carbon-carbon bonds in the polymer chains to produce lightweight molecules capable of being substituted for use in fuel feedstocks. To date, the process has been refined for the polymer cracking of PS, PET, PE, PP, and PVC [21]. The first requirement to begin this procedure is to separate the plastics into these plastic types, and then to shred them. Once separated and shredded, the plastics are melted and cracked. The resulting liquid is brown and at room temperature becomes a wax-like solid. This product is suitable to be mixed with standard feedstock streams. According to BP Chemical calculations, a single polymer cracking plant could recycle 20,000 metric tons per year of plastic [21]. This is roughly the volume of plastic disposed of annually by a city of 1 million inhabitants. According to BP Chemicals, this technology will be available to other petrochemical companies in the near future. BP is performing further research to incorporate more types of plastic feed that can be cracked in a similar manner, since currently mostly packaging materials can be used.

2.7 Recycled Materials Comparison

Steel recycling has been in existence for nearly 200 years, and has the highest recycling rate of any material in the United States [52]. Mainly, this recycled material is collected on the industrial level; however, recent aims have been made to incorporate household tin cans into this recycled material steam. The hopes are to remove this high profile steel waste from garbage piles, and increase it's recycled rate from currently 25% to 66%, the average rate for all steel recycled [52]. The main barrier steel recyclers have had to overcome to recycle tin cans, is a cost effective means to remove the tin coating covering the steel prior to its recycling. Once a method to do this has been universally implemented, over 3 million tons of steel scrap will be added to the approximately 60 million tons of steel now recycled annually [52].

The aluminum can recycling effort has had the most profound recycling results of any post consumer-recycling commodity. In 1990, 60% of all aluminum cans were being recycled, and it was predicted that over 70% would be by the end of the decade. In some geographical areas, such as New York City, recycling rates were reported in 1995 to be over 80% [52]. This rapid change in post-consumer aluminum can recycling habits have been boosted by lucrative monetary incentives paid to the consumers by the aluminum melting companies for the return of aluminum cans. The return of the cans enables the aluminum processing companies to save substantial money in energy costs by using post-consumer aluminum as feedstock. Because of this, aluminum has the highest price per weight of any post-consumer recyclable [52].

The glass bottle recycling effort has had a significantly less profound recycling results then either steel or aluminum has had. Glass recycling had very little growth, and only became a recognized 100% recyclable material after this was announced by the U.S.

Department of Commerce in 1990 [52]. Currently, the glass container production industry would have to more then double its use of recycled glass before the percentage of recycled glass used in the production of new glass containers would even approach 70% [52]. The main reason glass is not reused is due to the limited economic advantages of using it as a feedstock source. The components used to make glass, sand, limestone, and soda ash, have a very inexpensive and easy to acquire, making the recycling of glass a less advantageous operation then other recyclable materials. The only recognizable advantages of recycling glass containers are the limited extension of furnace life, minimal energy savings, and the savings of approximately 1.2 million tons of virgin glass making materials [52].

The recycling of paper in the United States has earned us the term, "the Saudi Arabia of waste paper." In fact, waste paper is the number one U.S. export by weight [52]. Currently only one third of the paper used in the U.S. is recovered, of which 22 % is the amount exported. Because of the sheer volume of paper used in the United States annually, even at a 33% recycling rate, paper is the most recycled material in the United States and world [52]. A future goal of the paper industry is to raise the recycling rate to over 40%, or 40 million tons, annually by the year 2000. Even if this goal is achieved, analysts predict that because of the increase in paper usage, the 60 million tons of paper now disposed of in landfills annually will remain steady. Paper recycling efforts are limited to the high startup costs associated to the addition of de-inking facilities that must be added to paper mills in order to recycle used paper. Unlike the other recycled material industries, that do not require the installation of additional equipment to integrate the recycled material as a feedstock, the paper mills capable of using recycled material are currently running a full capacity. So, until more de-inking facilities are constructed, the paper industry will not be able to recycle any more paper then they already do.

Plastic usage in the United States has increased from approximately 3 billion pounds in 1958, to over 60 billion pounds in 1990, and its growth continues to increase at an average rate of 10.3 % annually [52]. Unlike other materials, the recycling methods for plastics are still developing. In 1988 plastic recycling had the lowest recycling rate of all recyclable commodities at 1.1%. In 1990 an aggressive recycling war was waged for the increase of plastics recycling. Along with industrial incentives, the main driving force behind the plastic recycling revolution was legislation. In 1990 alone, 33 states adopted laws requiring plastics to be separated from the waste steam and recycled. In some places within the United States, certain plastic package types were even banned [52]. In recent years, the plastic bottle industry has made the biggest effort to encourage the recycling of their products by offering monetary rewards for their return, and as a result now uses up to 50% recycled content in every new plastic bottle produced. Arguments have been made that plastics cannot be recycled back into the same product forever like other materials due to their inherent continuously degrading characteristics; however, significant effort is being made to develop new products made of purely recycled plastic material. These proposed materials include lumber board and other various composites that consist of commingled plastics and previously recycled plastic matter. The future of these innovative products relies on the construction industry and applications there as a building material. If implemented successfully, all recycled plastic material, theoretically, could be reused for decades.

3.0 Methodology

A methodology was designed for this project after the background research on the topics in the literature review and data gathered through interviews was performed. In this section we explain the disposal options that were identified by our research that are currently or could potentially be performed, and the method for analysis and comparison of disposal options.

3.1 Identification and analysis of disposal options

In the results section, the goals of each process are described, and a description of the process is given. Analysis was performed in each process relating to the amounts of material used, products produced, waste produced, energy produced, and then economical considerations were performed to evaluate and compare each option. Environmental implications were taken into account. In performing our background research, the options that were currently available to dispose of automotive plastics were identified, as well as emerging technologies. It was found that four major options exist for the disposal of automotive plastics: 1) landfilling; 2) incineration or energy recovery; 3) designing for disassembly; and 4) recycling ASR (Automobile Shredder Residue) or separating the plastics from ASR for recycling.

3.1.1 Landfilling

To gather data, numerous landfills were contacted for information on the cost to dispose of ASR into a landfill. The cost of collection and transportation was evaluated.

Existing as well as future legislation concerning landfills, such as landfill taxes was considered. In the case of landfilling, the amount of plastic per automobile was found, and the weight of ASR generated from X automobiles was calculated. It was found that the cost to put the material into a landfill varies with location due to space available and taxes. The cost was evaluated for each of the areas where data was obtained. Use of ASR as a landfill cover was also evaluated.

3.1.2 Recycling of ASR

Argonne National Laboratory was contacted about the recycling of polyurethane foam from ASR to produce carpet padding or lumberboard, using a froth-floatation separation method. The recycling of ABS from ASR was also considered.

3.1.3 Energy Recovery

Incineration plants were contacted concerning the incineration or pyrolysis of ASR for information on energy recovery. The collection cost for the material being incinerated, including ASR, and the returns from the incineration, such as generating electricity. Environmental implications and the costs associated with pollution control and regulations were also considered. Legislation and environmental regulations relating to the profitability of incineration were evaluated. The collection cost of the material from X autos was evaluated as well as any special processing costs depending on the method being applied. The returns from energy produced by incineration were calculated. The profitability of this method to dispose of X autos was compared to the profitability of the other methods when disposing of X autos.

3.1.4 Design for Disassembly

The process of designing automobiles for disassembly was evaluated. People from corporations dealing with the collection of automobiles for the purpose of recycling used parts were interviewed to obtain data. This interviewing process included automotive dismantlers, recyclers, and manufacturers. The purpose of these interviews was to find what current methods were profitable in obtaining plastics by disassembling them from automobiles, and compare them to the recyclability of metal parts of automobiles was made. The labor costs to disassemble and separate the plastics were evaluated, and the returns from the dismantled plastics were assessed. Legislation relating to disassembly and the recycling of automotive plastics evaluated. Companies in the automobile manufacturing industry were contacted to find methods to make automobile plastics more easily recyclable, such as consolidating plastic types used, and designing for easy disassembly. An evaluation of what costs and trade-offs had to be made in order to make changes for design for design was attempted. Automobile manufacturers were contacted about their use of recycled plastics, and the parts can be made using recycled plastics were found. The users and processors of recycled plastics were contacted to find what changes could be made in order to make the use of recycled automotive plastic easier and more widespread. Methods to separate plastics were evaluated, since in many applications a high degree of purity is required.

3.2 Research Methodology

In addition to library research, two modes of communication were utilized in order to obtain our information, interviews and e-mail correspondence. The local Yellow pages for the Worcester and surrounding areas were used to find companies related to landfilling, ASR recycling, incineration, and design for disassembly. These companies were contacted by phone and specific questions for our project related to that company was asked. In some cases, we were referred from one company to another that was more directly related to our topic.

Personal Contacts by e-mail in order to obtain information were found by performing searches on the World Wide Web. Companies that were related to landfilling, ASR recycling, incineration, and design for disassembly were sent an e-mail asking the specific questions for our project that were related to that company. In some cases we were given a phone number of a personal contact, or directed to another web page with some of the relevant information.

A "reference sampling" technique was performed and information was obtained on each topic from a number of different sources. This process of gathering information on a topic continued until very little new information was being obtained, and the information from sources was beginning to be repetitive.

3.2.1 Interviewing Technique

An interview is a process used to ask a series of questions in a formal situation, usually in order to obtain information about a person or subject. There are a several types of interviewing methods that are used: standard, non-standard, and semi-standard. A semi-standard interview type of interview was used for this project [15].

The first type of interview is a standardized interview. This interview uses a formal structure and has a strict order of questions that are not changed. This type of interview is very rigid and does not leave room for follow up questions or digression from the preset set of questions. It is effective for comparing the results of interviews and determining how different groups of people or companies handle certain issues [15].

The second type of interview is a non-standardized type of interview, which is opposite in nature to the standardized interview. This type of interview is useful when the interviewer is not sure what type of questions should be asked at the interview. The non-standardized interview format has a lot of flexibility for follow up questions and leaves room for the interview to go in directions not anticipated by the interviewer [15].

The third and last type of interview is the semi-standardized interview, which is a hybrid of the first two types. This type of interview is a best-of-both-worlds type of interview. The interviewer heads to the interview with a pre-determined list of questions, but leaves himself open for follow up questions and any extra information that was not anticipated before the interview [15].

The type of interview that would be most appropriate for the IQP was the semi-standardized interview. The semi-standardized interview allows the group to go to an interview with a predetermined set of questions, while keeping flexibility and allowing follow up on any interesting information that has come up during the interview.

There are some points we kept in mind to make the interview session go smoother. First, background information was gathered before going to the interview.

This was done by searching for unbiased information concerning the topic. Also, it was imperative we knew the specific purpose for the interview. This way we had some time to prepare for what they had to say [14].

The interviews were not a dialogue. The interview was a chance to get as much information as possible from the subject. The interviewer's remarks were limited to a few pleasantries to break the ice and questions to guide the subject [13].

The questions that were asked should leave some room for the subject to work with. The questions asked “why”, “how”, “where” and “what kind of….” If “yes” and “no” questions are asked, the subject usually just gave a one-word answer instead of providing details [13].

There are four main types of questions were asked at interviews. They include essential, extra, throwaway, and probing questions. Essential questions exclusively concern the central focus of the study. These questions are intended to elicit specific answers from the subject. They are usually sprinkled throughout the interview and are not too prevalent [15].

Extra questions are those that are thrown in to verify the answers given to the essential questions. They ask for the same information as the essential questions, but in a different way to verify what the subject has already said. They are thrown in to make sure that the subject does not change his or her story [15].

Probing questions are questions intended to do exactly what their name implies, probe the subject for more complete answers to the questions. Probing questions are generally follow-up questions intended to get a more detailed response on a specific topic of the interview [15].

Throwaway questions are questions that are used to break the ice between the interviewer and the subject. These are generally demographic-type questions that don't have much bearing on the actual interview content [15].

Before conducting the interview, we arranged the questions in an effective order. The initial questions were the throwaway questions to ease the subject into the conversation, and make them feel comfortable. The more controversial probing questions were asked afterward. During the interview it was important to take simple notes.

Another point we kept in mind was that the interviewee should not be interrupted while they are talking because they are straying from the planned outline. If the information was pertinent, we let them go on, and wrote down any questions that came up on a notepad so that they could be asked at a later time [13].

During the interview periods of silence did not necessarily mean that the next question needs to be asked right away. The subject was given some time to collect his or her thoughts so that they could present their ideas the way that was best for them [13].

In the interviewing process, we found that putting a negative spin on a question actually works better then putting a positive spin on it. If given the positive aspects of a situation the interviewee will most likely agree even though they may not fully agree. Instead, it was best to start out by giving some of the negative aspects of a situation. This gives the subject either a chance to come to the defense of the topic, or add his or her own critiques to what has already been stated [13].

The subject was not challenged on any information that may seem inaccurate. This might make the subject uncomfortable and therefore, they may not share as much information. Instead, it was better to tactfully point out that there are some differing accounts of the information [13].

After the interview is over, it was best to write down notes from the interview while it was still fresh. If there was confusion about an important point, it was noted and the subject was contacted again to clarify that point or to ask some more follow up questions [14].

All of the previous information we used in this study can be summed up by "The Ten Commandments of Interviewing" given by Berg [15].

1. *Never begin an interview cold.* Always start off with some small talk to set yourself and the subject at ease.
2. *Remember your purpose.* Keep the questions and the narrator on track.
3. *Present a natural front.* Be relaxed and don't make the interview seem to rehearsed.
4. *Demonstrate aware hearing.* Make sure that you offer your subject the appropriate verbal responses so that they know you are listening.
5. *Think about appearance.* Make sure that you have dressed appropriately for both the situation and the subject you are interviewing.
6. *Interview in a comfortable place.* Make sure that the subject feels comfortable at wherever you decide to hold the interview.
7. *Don't be satisfied with monosyllabic answers.* Be aware of what type of answers the subject is giving you.
8. *Be Respectful.* Make sure that the subject feels that he or she is an integral part of your research.
9. *Practice, practice, and practice some more.* The only way to become proficient at interviewing is to go out and interview.

10. *Be cordial and appreciative.* Make sure that you remember to thank the subject when the interview is finished, and answer any questions that he or she may have about your research.

3.3 Analysis of Cost Comparison of Options and Environmental Impact

The method used in this project to compare the disposal options of automotive plastics was to calculate the economic monetary returns (or losses) for disposing of the automotive plastic from X automobiles, by each of the options considered in this project, and then compare the results. Environmental implications were also discussed.

For landfilling, the cost of collection and transportation of (\$trans/Y kg) of material was found, and multiplied by the weight (W kg/auto) of ASR generated by X automobiles, giving:

$$\$trans = \frac{\$trans}{Ykg}\frac{Wkg}{auto}XAuto$$

The cost to landfill the material is:

$$\$landfill = \frac{\$fill}{ton}\frac{ton}{Zkg}\frac{Wkg}{auto}Xautos$$

plus any costs due to landfill taxes or similar legislation:

$$\$legislation = \frac{\$tax}{ton}\frac{Zkg}{ton}\frac{Wkg}{auto}Xautos$$

The total loss for landfill is then:

$$\$landfill\_Xautos = \$trans + \$fill + \$tax = Xautos\frac{Wkg}{auto}\left(\frac{\$}{Ykg} + \frac{Zkg}{ton}\left\{\frac{\$fill}{ton} + \frac{\$tax}{ton}\right\}\right)$$

In the process of landfilling ASR, none of the material is recycled.

For Recycling of ASR, the costs of transporting the ASR raw material from X autos are calculated the same way as for transportation costs for landfills. The costs of separation and regeneration for plastics from ASR from X autos are estimated, and the monetary return from the amount of final product that can be produced from the amount of ASR from X autos is calculated. The cost to dispose of waste products is then added as a landfill cost. The returns for recycling of ASR is then:

$$\$recycle\_Xautos = \left(\frac{\$return}{kg\_product} \frac{kg\_product\_made}{kgASR} \frac{Wkg}{auto} Xautos \right) - \$trans - \$landfill - \$process$$

When plastic materials are recovered from ASR and recycled most of the ASR is usually not recycled and disposed of in landfills.

For the incineration of ASR, the costs for transportation are calculated the same as for landfills. The returns for incineration are calculated from the energy recovered. The remaining ash and non-combustibles still have to be landfilled. Environmental control equipment is another large capital cost. Only the combustible portion of ASR is incinerated, and the remaining portion of ASR must still be landfilled. The equation for the monetary returns from incineration of X autos is as follows:

$$\$incinerate\_Xautos = \left(\frac{\$value}{Btu} \frac{Btu\_of\_Plastic}{kg} wt\%Plastic\_in\_ASR \frac{WkgASR}{auto} Xautos \right) - \$landfill - Capital\_\cos ts$$

Returns for design for disassembly for plastic automotive parts and metal parts can be calculated as follows:

$$\$dissasembly\_Xautos = \left(\frac{\$return}{kgplastics} \frac{kgplastic\_recovered}{auto} Xautos \right) + \left(\frac{\$return}{kgmetals} \frac{kgmetals\_recovered}{auto} Xautos \right) -$$

$$\left(\frac{\$labor}{hour} \frac{hours\_to\_dissasemble}{auto} Xautos \right) - (disposal\_\cos t)$$

The amount of material recycled by disassembly depends on the degree to which the automobiles are disassembled.

In each of the above cases the returns (or losses) for each case was calculated, and compared. It will be noted in the results which factors may vary and make one method more cost effective than another for different conditions.

4.0 Results

In this section, the data obtained will be presented and analyzed. The data obtained was organized into the four major categories for disposal options of automotive plastics. These four major categories are: 1) landfilling ASR; 2) recycling of ASR; 3) energy recovery; and 4) design for disassembly.

4.1 Landfilling ASR

Presently each year in the United States, 10 to 11 million vehicles are taken out of circulation and disposed. A network of salvage and shredder facilities process nearly 99% of these vehicles, removing primarily the metals for recycling [25]. The non-recycled amount accounts for approximately 75% of the volume, or 25% of the vehicle weight. This waste is primarily in the form of automotive shredder residue (ASR), and at the present time, nearly 100% of it ends up in landfills. This total amount was calculated in this project by assuming an average of 500 pounds of ASR produced per automobile. Multiplying 500 pounds /automobile by 11 million cars discarded annually, it can be calculated that approximately 3 million tons of ASR end up in landfills per year. This accounts for approximately 2% by mass of all landfill material in the United States [24]. Knowing that ASR consists of plastics by approximately 42% by weight [27], and 36% by volume [28], it can be determined that 1.3 million tons of automotive plastics end up in landfills each year.

In North America, the cost of landfilling ASR is considerably less than the cost imposed in Europe. In the Eastern United States the cost of landfilling ASR ranges from approximately $12-$20/ton [28], which is relatively cheap compared to the price of landfilling conventional household trash, which is approximately $110/ton. In comparison, the prices of landfilling ASR in Europe can range anywhere from $60-$200/ton [30]. In Europe, landfilling is a less cost-effective solution than in the United States. This drastic difference in prices is the driving force behind alternative solutions for ASR disposal now being sought in Europe. With eight to nine million tons of automotive waste being generated annually in Europe alone, landfilling all this waste is not likely to be economical [31].

The primary reason landfilling remains a common and economical practice in the United States is due to the vast space available for landfills. It has been calculated that at the current rate of waste generation, all of America's garbage for the next thousand years will fit into a landfill measuring 120 feet deep by 144 square miles. This is approximately the dimension of three average size cities [32]. Although, this may be an underestimate and the source may be biased. Despite this calculated abundance of landfill space, the United States has made significant efforts to recycle, and in 1996 only 116 million tons of garbage went to landfills versus 140 million tons in 1990 [33]. These statistics only further encourage the landfilling practice of American society.

ASR's lower price per ton compared to household waste is due to an innovative technique developed to use ASR as a cover material for landfills [31]. At the Institute for Chemical Process and Environmental Technology (ICPET), it was demonstrated that ASR is an excellent absorbent of heavy metals. Due to ASR's propensity to retain heavy metals that can leach into soils and nearby water sources at landfill sites, this use as a cover material has been shown to be environmentally beneficial [31]. ASR is applied as a cover material for trash to be deposited upon initially, then applied daily as a cover coat to reduce odors, insects, and unsightliness associated with landfills. ASR also has some other advantages over household waste. ASR is highly compressible, so it reduces the overall volume of the landfill cell. It is also able to speed up drainage. ASR can also be used in landfills to facilitate better traction for the landfill equipment [32].

4.2 Recycling of ASR

In the United States there is a network of approximately 12,000 salvage facilities and 182 shredders that process these automobiles. Each year, this network processes approximately 10 million vehicles, generating more than 450 million cubic feet of ASR. Right now, in 2000, the accepted practice is to dispose of ASR in landfills [29].

Although vehicle shredding may efficiently separate metals from non-metals and ferrous from nonferrous metals, it does not preserve the greatest material value. The most notable loss in the "ASR waste stream" is a mixture of plastics and other recyclable materials that have been ground together so that the individual materials no longer have any commercial value. Recycling of ASR attempts to purify and reuse the components found in ASR. The chart below separates ASR into its different components by volume percentage [34].

PU-foam	5%
Plastics/elastomeres	31%
Non-magnetic fines	26%
Magnetic fines	18%
Fibers	10%
Stones/wood/dirt...	10%
Total	100%

Figure 1- ASR Breakdown by Volume Percentage [34]

There are several methods currently being evaluated as recycling methods for ASR. Some of these methods include usage as a cover material for landfills and alternatives to topsoil as described in the previous section, recycling the plastics in ASR into foam padding for carpets and car seats, as well as possibly recycling it into ABS.

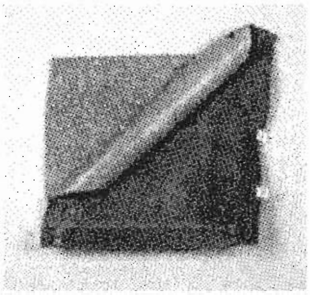


Figure 2. Soundproofing mats in vehicles [29]

Toyota has begun using a new technology to extract polyurethane foam and fabric granules from the residue of automotive scrap shredders. The material that Toyota extracts from the shredder residue becomes raw material for soundproofing mats that it installs in its vehicles (figure 2) [29].

Argonne National Laboratories has developed another process that can be used for the recycling of ASR. This process also recovers polyurethane foam (PUF) from ASR. The resulting product meets the performance criteria for new-material carpet padding and for reuse in automotive applications. Clean recycled foam sells for \$ .25-\$

.30 per pound, compared to more than $1.00 per pound for virgin material [34]. With this rate of return, it would take a little over two years to make back all of the capital costs of equipment for the operation [35].

4.2.1 Polyurethane Foam Recovery

This method for recycling ASR begins with mechanical/physical separation of the ASR into several factions: polyurethane foam, which is separated and cleaned, iron-oxide-rich fines which may be used by the cement industry as a source of iron oxide, and a plastics rich stream, from which Argonne dissolves and recovers heat formed plastics (thermoplastics). The solvent that is used in this process is regenerated and continuously recycled [36].

After the ASR is broken down into those three components, the PUF is cleaned in a process of six steps. 1) PUF recovery and screening, 2) sizing, 3) washing, 4) rinsing, 5) drying, and 6) baling. The process is fully continuous to minimize materials handling and labor costs. A unique trommel, equipped with longitudinal slots to reject all material less than a specific size, is used to recover any oversized material from the residue. As the PUF exits the trommel, an air knife is used to isolate it from the residual material. Following size reduction, washing, and rinsing, a unique dryer is used that reduces the drying time from about 3.5 hours in conventional dryers to less than 15 minutes. The clean, dry foam is then baled for shipment [34].

Design of a full-scale demonstration plant is under way. Argonne's first international partner to participate in a full-scale demonstration and to try to commercialize this process is a Belgian company. This company is specialized in the recycling of ASR [34].

4.2.2 ABS Recovery

Argonne Labs is also evaluating recovery of ABS plastic from the recycling process of ASR. The only problem with this process is that the ABS needs to be 99.5% pure in order for the recycling to be effective. It is very difficult to extract ABS from ASR with this kind of purity. The recycling of ABS has, however, been successfully completed from scrapped household items such as refrigerators and toasters. In this process the recycled ABS brings in anywhere from $ .25 to $.45 per pound. If a means were made available to extract pure ABS, this recycling could become a profitable venture [35]. Methods to do this are presently being evaluated.

Table 1 below shows a comparison of ASR between Europe, the United States, and various other countries. It breaks down the amount of cars that are being used, and how many are End of Life Vehicles (ELV's). It also breaks down the amount of ASR per vehicle as well as the total amount of ASR per country. The rest of the chart is the amount of various materials that can be found in the ASR [35].

	E.U.	U.S.	OTHER	TOTAL
Numbers of cars	154,000,000	121,000,000	200,000,000	475,000,000
Numbers of ELV's	14,000,000	11,000,000	15,000,000	40,000,000
ASR each ELV	220 kg	220 kg	220 kg	220 kg
Tons of ASR	3,080,000	2,420,000	3,300,000	8,800,000
Tons of PU foam	154	121	165	440
Tons of PVC	150.64	11.36	161.4	430.4
Tons of PP	132.3	103.95	141.75	378
Tons of ABS	92.45	72.71	99.15	264.4
Tons of PA	61.18	48.07	65.55	174.8
Tons of PE	38.5	30.25	41.25	110
Tons of PUR	189	148.5	202.5	540
Tons of Elastomeres	108.5	85.25	116.25	310
Tons of Other plastics	182.7	143.55	195.75	522
Tons of fines	1,355,200	1,064,800	1,452,000	3,872,000
Tons of fibers	308	242	330	880
Tons of stones/wood/..	308	242	330	880

Table 1- ASR Statistics by Region for End of Life Vehicles (ELV's) in 1999 [33].

4.3 Energy Recovery

One disposal method for ASR and automotive plastics is recovery of energy from the material. Incineration reduces the amount of material sent to landfills dramatically, and may also be used to produce energy. A number of different methods have been involved in order to recovery energy from plastics, including use as a substitute fuel, pyrolysis, and incineration. Transportation costs to bring materials to the incineration or process site are similar to those of landfill material transportation costs. Incineration plants designed for household garbage are not adequate for the incineration of ASR due to its high heat value and high metal content [37]; therefore, a specialized incineration method must be used.

German steel-making companies Stahlwerke Bremen and Krupp-Hoesch have equipment to substitute granulated plastic in the place of heavy oil in their steel-making process. At Krupp-Hoesch, granulated plastic is injected into the furnace by the same methods used to inject fine coal, leading to saving on capital equipment costs. Testing was performed on emissions since toxic materials may be formed due to the incineration of PVC (polyvinyl chloride). The emission of dioxins due to incineration of PVC's was well below Germany's federal emission limit for incineration plants due to the high temperatures used in this application (up to 2200 C) [38]. Emissions of other pollutants such as carbon dioxide and methane were similar to when using heavy oil as a fuel. This process, however, has not yet been attempted using plastics obtained from ASR.

Similarly, at Stahlwerke Bremen, oil that costs about $100/ton is replaced by plastics for which the company is paid $133/ton to take. The capital equipment costs at Stahlwerke Bremen to implement the system were about $33 million, whereas at Krupp-

Hoesch techniques were developed to avoid major capital costs of new equipment [38]. This process development was funded by licensing fees paid by plastic packaging manufacturers to the non-profit corporation Duales System Deutschland GmbH that seeks to avoid waste and to recycle materials. At Stahlwerke Bremen, thirty percent of the energy of the plastic is used thermally, and fifty percent is used in ore reduction for an overall efficiency of 80% [38].

Companies such as EnerWaste Incinerator Systems can build incinerators for disposal of ASR. EnerWaste system capacity may range from 0.5-60 tons/hour, and can be made to be fully automated, which include pollution control devices such as scrubbers, filters, and electrostatic precipitation devices [39]. Similar methods such as an auger combustion process manufactured by Environmental Improvement Systems can be used for ASR. In this method, the incinerator has an auger inside to move the ASR while heating it to gassification temperatures. The ash is moved out of the reactor and collected by the auger. The gasses produced proceed to an afterburner in which they are burned.

Pyrolysis is another method used to obtain useful products and energy from ASR. In the process of pyrolysis, the ASR is kept under a high vacuum and the temperature is increased. This produces vapors from the organic materials, charcoal, and residual metallic solid material. Some of the vapors are condensed to oil. The oil and gas products produced are similar to natural gas and heavy crude oil. Additional treatment would have to be performed before using these products to make plastic in the chemical industry [40]. Since ASR is a non-biodegradable waste and is considered toxic or hazardous waste in some areas, pyrolysis is typically a more attractive solution than incineration [41].

In the research conducted by Allison Altschuller [40], the final components from pyrolysis of ASR were 50-70% residual solid, 7-23% pyrogas, 1% oil, and the remainder was water. This was different than the products obtained by E.T.P. Technologies, which were 18.3% oils, 8.8% iron, 7.3% metal alloys, 37.5% inorganic materials, 8.4% charcoal, 3.9% gas, and 15.8% water [41]. These differences may be due to differences in the systems used.

An estimation of the capital cost for pyrolysis was determined to be one to two million dollars [40]. A benefit of pyrolysis is that it defers some of the cost of landfilling materials, but is not profitable by itself. Pyrolysis would be expected to have a lower profit margin than shredders, making it unlikely that shredding companies would venture into pyrolysis [40]. Pyrolysis may be more useful in Europe where landfill costs are higher and there may be mandatory take-back or recyclability-content legislation passed.

Environmental benefits of pyrolysis are reduced landfill space, as well as oil/gas produced which can be integrated into feed streams of chemical plants. Pyrolysis must be examined for the dangers of toxic components created from plastics containing chlorine (such as PVC).

A joint effort by Universite Laval and E.T.P. Technologies, Inc. in Quebec has constructed a pilot plant for pyrolysis of ASR, as well as an economic evaluation for a scaled-up process. Testing at E.T.P. Technologies consisted of analysis of a 25 kg sample of ASR. Larger pieces of ASR are further shredded and placed into the beds of the reactor. The temperature and pressure of the reactor were set to 1.5 kPa and 530 C. The gas formed was pumped to cooling towers for condensation and gas purification, and non-condensable vapors were analyzed by gas chromatography. It was noted that the oil yield was greater when a higher portion of rubber was used in the feedstock. Solid material was analyzed by atomic absorption to determine chemical compositions. Metals in the solid material may be recaptured. The fluff volume was reduced by 3.7 times the original feedstock [41]. The oils produced have a high heating value and low sulfur content, but have trace or small amounts of heavy metals, especially iron. Water is easily separated from the oil by decantation. Treatment of the oils can make it a substitute for No. 6 fuel oil. The gas produced has a high heating value due to its high hydrogen content.

The industrial process was designed for 4000 kg/hr, with a fixed capital investment of about $5 million (US). The assumptions made were that the plant was running 24hrs/day 330 days/year, they were paid $15/ton to take ASR, oil can be sold at $13/bbl, ferrous metals sold at $42/ton, non-ferrous alloys sold at $680/ton, and gas sales at $.075/kg (75% of the price of natural gas). It was evaluated that a return on the investment of 17% before tax, and a profit of $27/ton is possible [41].

4.4 Design for Disassembly

Design for disassembly, also termed design for recyclability or green engineering, is a relatively new tool that is being implemented today in many new car designs by automotive manufacturers as a means to reduce automotive shredder residue generated by end of life vehicles. The idea is to design automobiles with the goal to make them as simple to disassemble as possible, and use materials that once sorted can be easily recycled using current recycling technologies. Since this type of engineering is relatively new to the automotive industry, no economic elements associated with its implementation have yet been realized; however, certain criteria have been proposed to successfully apply this idea.

Design for recyclability criteria has been specified by Environmental Defense [42]:

Use Recyclable Materials- Design automobiles that use materials that can be recycled using current technology and for which those materials currently exist. In the case of plastics, thermoplastic resins should be chosen over thermoset plastics whenever possible.

Use Recycled Materials- Select and use materials that have some percentage of recycled content, hence supporting the recycling process and economically encouraging supply of recycled materials.

Reduce the Types of Materials Selected (Used)- Reduce the number of different materials used to manufacture an automobile. This will simplify the separation process and support recycling technologies.

Mark Parts for Identification- Mark all automobile parts with standard material identification codes. This should include all plastics, metals, composites, and coatings used in the vehicle's manufacturing.

Use Compatible Materials- Select materials that do not need to be separated for recycling. Use plastics and metals of similar types so that contamination will be eliminated upon recycling. Paints should also be chosen carefully, to reduce their chances of being a contaminant to the recycled material on which it is applied.

Make it Easy to Disassemble- Make disassembly as simple as possible. Use of snap nuts as well as common nut/bolt assembly techniques will make removal of parts much simpler than using adhesives as well as reduce the chances of contamination.

To make design for disassembly successful, all six techniques must be applied simultaneously and not individually. For example, in the case where materials are selected that can be recycled using current technology, but cannot be easily removed from the vehicle due to the use of adhesives, design for disassembly fails.

Dealing with this problem today from a disassembly aspect is much more complex and less rewarding financially than the future of Design-for-Disassembly will most likely be. Today, the North America automobile recycling industry employs approximately 80,000 people and grosses $4 billion in annual sales [45]. In the majority of cases for this industry, this is done in the following fashion: used automobiles are auctioned off near the end of their life to dismantling companies and part suppliers. The average cost per automobile bought at an auction ranges from $25.00 to $7000.00 [51]. Once acquired, the automobiles are dismantled and sold to buyers who call asking for specific parts. In general, about 50% of the parts removed are sold to remanufacturers, with the remaining 50% going to private buyers. An average of 40% profit is made per automobile, with almost all of the profit coming from non-plastic type parts. Plastic parts are rarely recovered for reuse after being damaged [51]. An average cost of $7-$11 an hour is paid to the workers involved with the disassembly and removal of the automobile parts [51]. Since plastic is not a valuable commodity, the economics to remove them prior to shredding for the purpose of recycling is not cost effective. If full recycling of automobile plastics were achieved, nearly 85 million barrels of oil would be saved from use in the United States [45]. However, until full disassembly and methods to sort and recycle the plastic parts are achieved, this will remain unchanged.

Design for disassembly has been a slow movement in North America, incorporated into some automobile manufacturer designs only recently, primarily due to the low costs for ASR disposal and lack of government regulations. In Europe and Japan, however, Design-for-Disassembly has made great headway due to economic factors not present in North America. In Germany, a piece of legislation, The Packaging Ordinance of 1991, was put into effect holding producers responsible for packaging waste precluding the use of public money for its disposal [43]. This legislation was catalyzed by the increasing shortage of landfill space in Germany. Shifting the costs of collection, sorting and the recycling of used packaging from the government to private industry, new methods were quickly applied by manufacturers to make their products as simple and cost effective to recycle as possible. Industry responded by designing the Green Dot System, which established a company, Duales System Deutschland, that collects, sorts, and directs waste material to recyclers. A fee is then calculated by weight and is paid by the company from which the waste product came. Between 1991 and 1994 packaging consumption in Germany decreased by 1 million tons each year [42]. Although currently only industries using packaging for their products are required to make this effort to recycle 100% of their waste, legislation is being proposed for other industries including automobile manufacturers. With the threat of this legislation being applied to the automobile industry, BMW, Volvo, and Volkswagen placed an extensive effort into the implementation of Design-for-Disassembly in their automobile designs, as well as organized many dismantling companies that dismantle the automobile and either return the parts to the auto manufacturer, or sell the material to the appropriate recycling organization [42].

Since the revolutionary Packaging Ordinance of 1991 in Germany, most European countries as well as Japan have implemented similar packaging type legislation holding manufacturers responsible for disposal of their products at the end of their life [43]. In most cases, like Germany, automobile manufactures are not yet required to take back their End of Life Vehicles; however, with impending legislation in the works for most, European and Japanese automobile manufactures have taken similar steps to incorporate Design-for-Disassembly into their vehicle designs. For example, in Japan, Nissan Motor Company has started an initiative to take back and recycle specifically selected plastic parts from their automobiles. Currently this includes bumper fascias, instrument panels, ventilation ducts, and floor carpet [44]. By starting small, Nissan plans to establish a value for recycled materials, assure a continuous incoming supply of recycled materials, and identify any potential problems as well as aid in the Design-for-Disassembly of future products [44]. They ultimately plan to make a smooth transition into 100% recycling operations for their automobiles.

In the United States similar legislation was proposed for the packaging industry and submitted to Congress in 1992 in the Resource Conservation and Recovery Act [43]. Although this Act was defeated, many United States companies have taken it upon themselves to improve the recyclability of their products. The Ford Motor Company and Saturn have initiated bumper take back programs [47]. Another company involved with this area of the market is a corporation called Keystone. Keystone acquires used or damaged bumpers from auto body shops at no cost, and attempts to repair them for after market reconditioned resale purposes. The heavily damaged bumper fascias must be scrapped; if more than $30 needs to be applied to a bumper fascia to make it suitable for resale, then can a profit cannot be made [50]. While these attempts to recycle bumper fascias are relatively new and only recycle a very small percentage of the total automotive plastic waste, they mark an effort by these companies towards recycling. Saturn (a subsidiary of General Motors Corporation) has gone a step farther, initiating a "Design for the Environment Policy" and attempting to build an automobile that is potentially 99% recyclable [45].

The "Design for the Environment Policy" initiated by Saturn is a comprehensive design policy that appears to make an obvious attempt at applying the six fundamentals of Design-for-Disassembly to current production automobiles. Saturn uses two-to-four mass percent more plastic per automobile than other manufacturers. Although currently many different plastic types are used, Saturn is attempting to consolidate their selection to include primarily olefins [48]. Of the plastics used, all have some recycled content. In fact, Saturn is continuously increasing the amount of recycled content used in the vehicle lines [48]. In addition, Vehicle Technical Specifications are requiring that the recycled content increase with each subsequent vehicle design [48]. Various suppliers are involved with supplying the recycled resins. The thought on the issues by both GM and Ford is that continued demand of recycled resins will create a larger free market in this area of industry, and increase post consumer plastic recycling [49].

Currently, both thermosets as well as thermoplastics are used in all cars; however, more thermoplastics are used than thermosets (excluding the corvette). In addition, Saturn utilizes the globally recognized ISO011469 marking standards to label all parts on their vehicles in hopes of making recycling much easier for the End of Life Vehicle. In addition, Saturn's Design Release Engineers are taught in a newly developed GM training course, entitled "Design for Recyclability," to make appropriate decisions when designing their automobiles. While these courses are a possible solution to the problems of automobile recycling, especially with a probable increase in plastic usage for future automobiles, benefits will not be able to be appreciated for approximately another 14 years, when the average automobile becomes an End of Life Vehicle [49].

There is at least one company that is exploring the aspect of full disassembly of automobiles to achieve a profit from nearly all the acquired parts, and reduce waste to less then 5% of the total automobile weight. This company is called Comprehensive Automotive Reclamation Services (CARS), located in Maryland. Using technology for dismantling developed in Holland, they have patented this technology and are attempting to reach a full-scale capacity of 30-40 cars per year per plant [45]. The company envisions a day in which they will have 100-150 such plants, and is capable of processing 50% of the United States End of Life Vehicles annually [45]. CARS is working with an outside company to develop a mixed plastic product derived from various automotive plastics since it may be many years before the recycling of individual plastics from automobiles may be possible [45].

5.0 Process Calculations

Due to the complexity regarding the full operation of each method being explored in the following section, some necessary assumptions have been made. This has been done to allow for economic and environmental comparisons. Any assumptions made have been stated as such and reflect actual data that was found during the research stage. The primary assumptions made were:

1) Common labor wages among different types of recycling operations
2) Average ASR landfill tipping fees used despite location
3) Negligible taxes and government regulation
4) Common overhead costs between recycling methods

Using these assumptions as common standards, the models became normalized and conclusions between then could be made. In the conclusion section comparisons were made that take into account the assumed variables for each model. Since each model represents a different method where certain assumptions may weight differently for one method over another, the conclusions attempt to bring a better understanding to each method, and under what conditions they would be best suited.

The following calculations in sections 5.2 through 5.4 do not take into account the money generated from the combined sales of parts by small auto dismantler businesses, and the average shredder facility profits mad by the sale of scrap steel. Section 5.5 describes a calculation for an innovative full-scale automotive disassembly plant that takes into account earnings for an automobile from it's purchase by the dismantler to full disassembly. In order to better compare sections 5.1 through 5.4 to those of 5.5, calculations have been conducted to show a total amount of annual earnings a typical shredder plant would make as well as the auto dismantlers who individually contribute to the shredder supply. From the amount of ASR generated by the average shredder annually at 6,000 pounds ASR per hour being 25% automobiles weight, with the rest being steel weight, it is calculated that 18,000 pounds of scrap steel is generated per hour. With the average car weighing 3,300 pounds and the shredder facility operates 24 hours a day 365 days a year, each shredder processes approximately 64,000 cars annually with an average steel scrap selling price in 1999 of $100 per ton [59], it is calculated that shredders make $7.9 million annually in steel scrap sales alone.

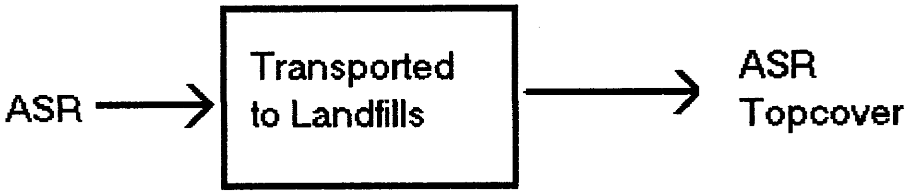
The supply of automobiles to shredders comes from an array of small automobile dismantlers. At an average purchasing price of $1,000 per automobile [51], the average automobile dismantler expects to make $3 for $1 spent [51]. Combining the profits of all the individual dismantler businesses providing a single shredder with scrapped automobiles, annual profits in sum come to $127 million. Combined with the sale of the steel scrap, the total net profits for the sold parts and scrapped steel providing for one shredder facility are approximately $135 million annually. Since section 5.5 details an innovative process that incorporates the total profits generated form non-plastic and plastic automobile material together, while the other sections do not, so it should be kept in mind that $135 million in profits are made prior to the final disposal methods analyzed in sections 5.1 through 5.4.

5.1 Landfilling ASR

5.1.1 Process Goals

The primary goal of landfilling is to dispose of ASR in a simple and inexpensive manner without the requirement of high overhead costs. The secondary goal is to use ASR as a substitute to soil at landfill sites for use as a top cover.

5.1.2 Process Flow Diagram



5.1.3 Process Analysis

ASR is generally inexpensive to dispose of in landfills because it can be used as a substitute for soil as a top cover material. The ASR is simply trucked from the shredder facility to the landfill and used as is. No further processing is required after leaving the shredder; hence capital and overhead costs are less than that required by other disposal methods. The cost to dispose of ASR in landfills is related to transportation costs and regional landfill tipping fees [40, 50, 51].

5.1.4 Economic Analysis

The cost of landfilling ASR is mainly dependent on geographic locations since areas with higher per-capita populations have higher trash disposal fees [53]. In January of 2000, in Massachusetts, it was found that the cost of disposing one ton of household trash costs $120/ton [28, 37]. This cost incorporated the trucking costs and the tipping fee since collection and disposal occurred locally. It was also found that ASR in this region costs $14/ton to dispose of in landfills [28]. This lower cost compared to household trash was due to the landfill's usage of the ASR as a top cover. This ratio of one-to-nine was found by computing the expected costs of ASR disposal compared to that of household trash within the US [28,53]. Using this factor in conjunction with Table 1, and other up-to-date landfill cost information the costs for disposing of the ASR in a particular region of the country can be estimated.

From Table 1 it can be noted that the Northeast has the highest landfill costs in the US. Despite these high costs, landfilling ASR in that region is still practiced. At some point in time, however, it may become more economical to truck the ASR to another region where landfill costs are lower. The equation below could be used to calculate when trucking to another region would become the economical choice.

Total Landfill Costs = Trucking Costs/Ton ASR + Landfill Tipping Fee/Ton ASR

Since it is still economical to landfill ASR in the Northeast where landfill-tipping fees are at their highest, the cost imposed on a shredding facility to dispose of the ASR annually by landfill can be approximated. It was calculated that the national average production of ASR per shredder is 6000 pounds hourly and it was computed that 26,280 tons of ASR is currently being disposed of by each shredder facility annually.

Table 1. Results from the National Solid Wastes Management Association's Tip Fee Surveys, 1985-1992

Region	Average tip fees, dollars per ton 1985	1986	1987	1988	1990	1992	Regional Population (1,000's) 1992	% of U.S. Population 1992
Northeast	$12.66	$17.11	$52.41	$61.11	$64.76	$65.83	31,319	12.5%
Mid-Atlantic	16.99	22.08	26.32	33.84	40.75	47.94	33,584	13.4%
South	3.24	5.76	13.13	16.46	16.92	22.48	46,214	18.4%
Mid-West	7.23	11.75	16.42	17.70	23.15	27.10	55,238	22.0%
West Central	5.36	6.21	7.23	8.50	11.06	12.62	12,049	4.8%
South Central	7.24	7.61	10.17	11.28	12.50	12.53	31,155	12.4%
West	10.96	11.10	13.92	19.45	25.63	27.92	41,374	16.5%
Total population (does not include Hawaii or Alaska)							250,933	

Regions:

Northeast:	Connecticut, Maine, Mass., New Hampshire, New York, Rhode Island, Vermont
Mid-Atlantic:	Delaware, Maryland, New Jersey, Penn., Virgina, West Virgina
South:	Alabama, Florida, Georgia, Kentucky, Miss., North Carolina, South Carolina, Tenn.
Mid-West:	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
West Central:	Colorado, Kansas, Montana, Nebraska, North Dakota, South Dakota, Utah, Wyoming
South Central:	Arizona, Arkansas, Louisanna, New Mexico, Oklahoma, Texas
West:	California, Idaho, Nevada, Oregon, Washington

Sources: Tip Fee Data: Edward Repa, "Landfill Tipping Fees, 1992," Waste Age, March 1993.
Regional Population: U.S. Statistical Abstract, 1993, Washington, DC; GPO, Table 31 Resident Population.

Table 1- Results from the National Solid Wastes Management Association's Tip Fee Surveys, 1985-1992 [53]

Applying the national average disposal fee for ASR in the United States of $12/ton [51, 53], yields that approximately $315,000 is paid by shredder facilities annually to dispose of ASR [24,29,35,38,40,42].

5.1.5 Environmental Analysis

Since no material or energy is recovered by the ASR disposal method of landfilling, this method does not recycle. This method of disposal generates pollution with approximately 5 million tons of waste going to landfills annually. One positive impact of ASR being landfilled is its suitability to be used as a cover material as a substitution to topsoil. ASR is not regarded as a hazardous material; however, some studies have shown it may be a contributor to ground water contamination due to the leaching of heavy metals from the ASR and into the landfill surroundings.

	Landfilling ASR
Economic Analysis	64,000 Cars Processed Annually
Calculated Capital Costs	$0 {It should be noted a shredder facility has a capital cost of ~$1.6 million}
Initial Profits Assuming: * = Capital Costs paid off by the 1st year ** = Capital Costs paid off by the 2nd year *** = Capital Costs paid off by the 5th year	$0
Annual Profits/Loss After Capital Costs are Paid	$315,000 Loss
Total Industry Profits including the sale of Steel Scrap and Parts	~$134,600,000
Most Significant Factor(s) that would Degrade Annual Profits	Increased Landfill Costs Increased Trucking Costs
Environmental Analysis	
Percentage of Automobile Plastics Recycled: * = material recycled for reuse ** = recycled by energy recovery	0%
Resulting Pollution Type	Nontoxic Landfill Waste

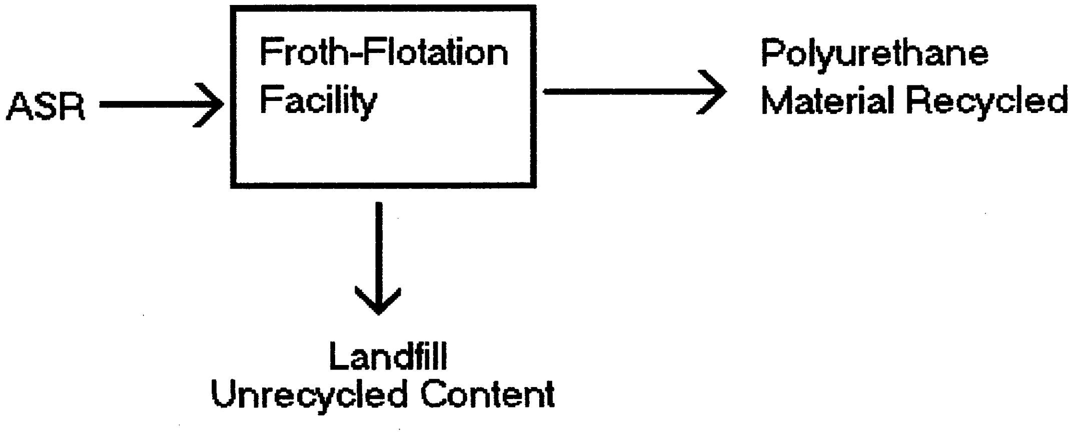
Table 2 - Summary of landfilling ASR results

5.2 Recycling ASR

5.2.1 Process Goals

The primary goal is to use a froth-flotation plant for the purpose of separating polyurethane from ASR. An increase in the price of oil will theoretically make this method more profitable over time as the price of virgin material increases with the price of oil. The recycled polyurethane can be reused for the production of carpet padding [44]. A secondary goal is to incorporate a method to also recycle ABS from ASR. This method is currently used with old household appliances, however, a 99.5% purity level must be met by the recycled ABS content, and this have yet to be achieved from ASR [35].

5.2.2 Process Flow Diagram



5.2.3 Process Analysis

This process uses a froth flotation facility to extract polyurethane foam from ASR. This method separates the polyurethane by chemically transforming it into a foamy state, which can then be mechanically removed from the surface of a bath. The foam is then cleaned and resold for the construction of carpet padding. A similar method is used for the separation and recovery of ABS from used appliances. However, because ABS need be 99.5% pure for reuse, this is not yet achievable from ASR. More research must first be done before ABS can be recycled from ASR.

5.2.4 Economic Analysis

Polyurethane Foam

A total economic analysis for the recycling of polyurethane using a froth-flotation facility was attempted from figures acquired through phone interviews with Bassam Jody. Assuming small-scale facilities were constructed at individual shredder sites, a theoretical plant would need to process 6,000 pounds of ASR per hour, as was calculated previously. Since the PU foam is on average only 5% of the plastic mass in ASR, 95 pounds of PU foam could be recycled hourly [34]. At a typical recycled PU selling price of \$0.25/pound, in comparison to a virgin PU selling price of \$1.00/pound, it is estimated that a gross profit of \$208,000 could be generated from such a facility annually [35]. This profit would be affected drastically with the changes in oil prices, and larger profits would be generated as prices increase. As was indicated by the project leader, Bassam Jody [35], that in two years the profit generated would repay the capital costs. Therefore, it was evaluated that the initial cost to build such a plant would be approximately $416,000.

It is assumed that the facility would be operated continuously with a one-man crew for labor evaluation purposes [55]. Assuming technical knowledge and experience is needed by the operators, an expected wage would be about $14/hour, or approximately $123,000 spent annually on labor [55].

Since only a small portion of the ASR content will be recycled, a large percentage will still need to be sent to landfills. The plastic mass accounts for 30% of the ASR weight, and PU accounts for 5% of the plastic mass weight, so approximately 26,000 tons of ASR will still need to be landfilled annually by each PU facility [35]. Applying the national average tipping fee cost of $12/ton for ASR disposal in landfills, the cost to landfill the un-recycled ASR material would be roughly $312,000 [51,53].

Using the previous data, the following equation can be applied to achieve the total economic evaluation for a froth flotation facility:

$$\text{Total Profit} = \text{Polyurethane Sales} - (\text{Labor Costs} + \text{ASR Disposal} + \text{Additional Overhead Costs})$$

Assuming the polyurethane sales are used the first two years of the plants operation to repay the start up costs, and overhead costs are neglected, the total profit would be a negative amount (loss) of $435,000/year [35]. Two years after startup cost had been alleviated, and overhead costs again ignored, the total profit would still be a negative value (loss) of $227,000/year. Although this amount is a price paid by the shredder/froth flotation facility, it is still significantly less than what would have been paid out annually by landfilling the ASR. It was noted that an increase of only $.25/pound sale price of PU foam to \$.50/pound, would bring the amount lost to \$19,000/year. From calculations using the model, once a market selling value of recycled PU foam reached a critical value of \$0.53/pound, profits would begin to be generated from this process.

ABS

Little information is currently known about the recycling of ABS from ASR to do an economic evaluation for an ABS recycling recovering facility. However, if this method does become available, the addition of recycling ABS to a PU recycling facility would most likely result in a significant increase in profit made by the plant. Since ABS is 18% by mass on the average for the plastic content of ASR, approximately 324 pounds of ABS could be collected hourly [57]. At its current selling price of \$0.25/pound, the sales it alone would generate a sales profit of \$710,000/year. If this method could be successfully integrated with the PU recycling method to operate in a joint facility, profits would be realized. The total profit of a combined PU/ABS recycling facility would be in the neighborhood of \$ 43,000 for the first 2 years until the capital costs are paid, and increase to roughly \$500,000 after. These figures are speculative, and assume that the process is fully automated to reduce labor costs, overhead costs are ignored, and the startup costs are only slightly to \$500,000 to include the recycling of ABS.

5.2.5 Environmental Analysis

The environmental implications of using froth foam plants are that for PU recycling alone there would be 72,000 tons less ASR being sent to landfills annually. Although this might sound significant, it only accounts for a 1.4% recycling rate of ASR.

Incorporating a hypothetical ABS recycling system into this plant operation, a combined amount of 330,000 tons of ASR would be reduced from landfills, which is 6.6% of ASR.

Although this method shows a positive alternative by recycling some of the material from ASR, and hence reducing landfill waste, the chemicals used to perform the separation are toxic and require special handling. Because of this, this process might have other environment implications which have not yet been realized, resulting in consequences more drastic than putting the ASR into landfills.

	Recycling ASR (calculated at PU and ABS prices of $0.25/lb)
Economic Analysis	64,000 Cars Processed Annually
Calculated Capital Costs	PU: $416,000 PU/ABS: $900,000
Initial Profits Assuming: * = Capital Costs paid off by the 1st year ** = Capital Costs paid off by the 2nd year *** = Capital Costs paid off by the 5th year	PU: ** $435,000 Loss PU/ABS: ** $100,000 Profit
Annual Profits/Loss After Capital Costs are Paid	PU: $227,000 Loss PU/ABS: $500,000 Profit
Total Industry Profits including the sale of Steel Scrap and Parts	PU: $134,700,000 PU/ABS: $134,500,000
Most Significant Factor(s) that would Degrade Annual Profits	Decreased Oil Prices
Environmental Analysis	
Percentage of Automobile Plastics Recycled: * = material recycled for reuse ** = recycled by energy recovery	PU: *5% PU/ABS: *23%
Resulting Pollution Type	Toxic Solvent Used in Froth Flotation

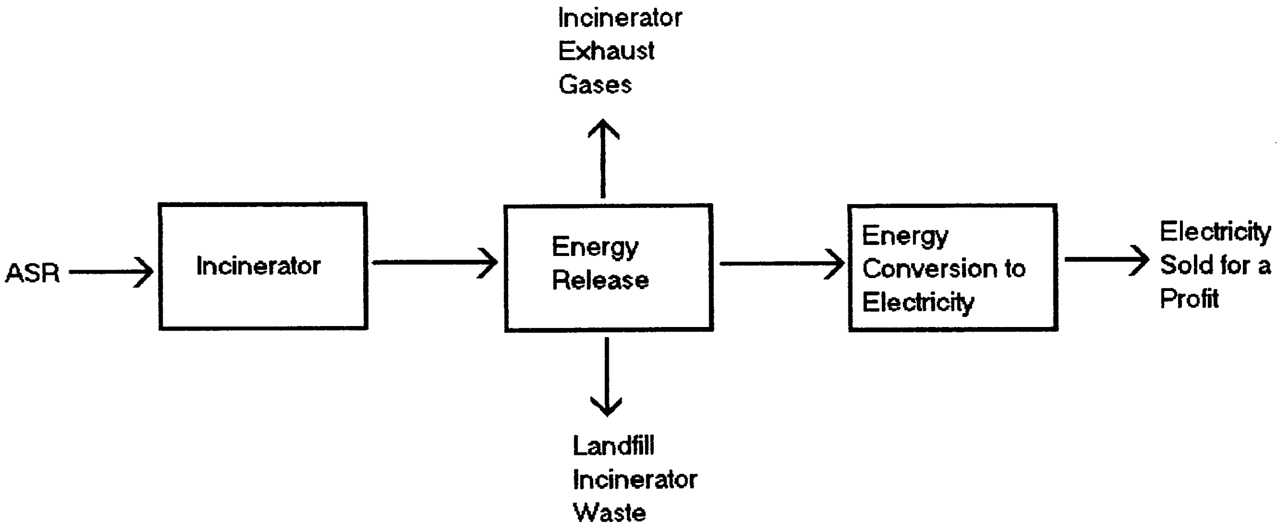
Table 3 - Summary of recycling ASR results

5.3 Energy Recovery by Incineration

5.3.1 Incineration Process Goals

The main goal of ASR incineration is to recover as much energy from the plastic material in ASR as possible to generate electricity. Secondary goals of this process are to reduce the volume of ASR sent to landfills annually, while attempting to minimize toxic emissions from the burning of the plastics in incinerators.

5.3.2 Process Flow Diagram



5.3.3 Process Analysis

In the US, 182 auto-shredders currently exist [29]. At an average of 5 million tons/year, or 10 billion pounds/year, approximately 27 million pounds of ASR is produced daily. This equals 150,000 pounds of ASR generated from each shredder daily. Assuming around the clock shredding operations, this calculates to 6,000 pounds of ASR per shredder per hour. Knowing that ASR contains thirty-percent plastics by weight, the amount of plastics produced in ASR is 1,900 pounds/hour.

With there processing requirement in mind, High Temp Technology Corp. was contacted to give an estimate of the cost of building such an incinerator. They recommended that a two-stage high temperature incinerator with a scrubber be used to significantly reduce toxic emissions from the combustion of the plastic material. For a high-temperature, two-stage incinerator alone capable of processing approximately 2,000 pounds/hour of combustible plastics, they indicated that the cost for the incinerator alone would be $448,000.00. The addition of a steam generator and scrubber would bring this total cost to $668,000.00. It should be noted that these costs are a result of manufacturing costs and marketing estimates and may or may not reflect actual cost [54]. The ASR incineration process was assumed to be built on site where ASR is generated.

High Temp Technology Corp. also computed an energy production calculation for the total incineration of plastic in the ASR. With an operating temperature of 1600°F and a water/steam temperature of 350°F, the incinerator will achieve an approach temperature of approximately 200°F. The approach temperature in this calculation signifies the relation between the actual and potential heat transfer between combusting materials and water temperature within the boiler. The industrial standard for a heat recovery boiler is 7 ft^2/bhp. Calculating the recovery factor as [54]:

$$\frac{[1600-(350+200)]}{(1600-70)}=68\%$$

This signifies that 68% of the total plastic energy will be recovered to generate electricity. With 1,900 pounds/hour of combustible plastic in ASR available,

$$1{,}900\frac{lbs}{hour}*10{,}000\frac{BTU}{lb}*68\%=12{,}920{,}000\frac{BTU}{hour}$$

roughly 13 million BTU/hour could be produced from the operation of the incinerator.

This operation would be self sufficient once operating temperatures have been achieved. The fuel used to get the reactor up to the operating temperatures is no longer needed due to the heat supplied by the combustion of the plastics. Theoretically a one-man crew would run the incinerator on a 24-hour basis indefinitely.

5.3.4 Economic Analysis

The economic analysis of this process incorporates startup costs, labor costs, and profits made by the sale of electricity. For electrical power production, the energy released by the incinerator must first be converted to watts/hour. The appropriate conversion to used was:

$$1.0watt=3.4\frac{BTU}{hour}$$

Applying this conversion to the 12,920,000 BTU/hour calculated for the previous section, the incinerator produces 3,800 kW/hour. Assuming the electricity can be sold for $0.06/kW [37], the incinerator will make approximately $228.00/hour from electricity sales. Calculating for a 24-hour operation, 365 days a year, the incinerator would generate electricity sales of 2 million dollars annually.

For labor purposes, it is assumed that the incinerator would be operated continuously with a two-man crew. Assuming, technical knowledge and experience is needed by the operators, an expected wage would be about $14/hour, which is approximately $250,000 spent annually on labor.

Knowing that ASR consists of 30% plastics by weight and assuming complete combustion of plastics, the total ASR ash that will need to be landfilled weighs 18,000 tons annually. Using the national average cost of $12/ton to landfill ASR, it was evaluated that it would cost $270,000 to dispose of ASR ash annually.

The economic evaluation of the incinerator can be broken down into the following equation:

Total Profit = Electricity Sales – (Labor Costs + Ash Disposal + Additional Overhead Costs)

Assuming that overhead costs for the first year are negligible in comparison to the capitol costs, and the capital costs were paid in the first year, the equation was used to find the total profit for the first year of operation were found to be $830,000. Once capital costs are repaid and assuming overhead costs are negligible in comparison to the other costs, the total profits are calculated to be $1,480,000 annually. The values are somewhat inflated because they do not take into account any other imposed fees that vary with location such as taxes, local or state permit fees, and land costs, and cannot easily be evaluated in a general manner. They will be addressed in the conclusions.

5.3.5 Environmental Analysis

The obvious environmental advantage of incinerating ASR is that energy is recovered from the plastic mass verses sending it to landfills. As was calculated in the process analysis, this energy recovery can be achieved with a recovery rate of 68%.

The disadvantage of incinerating ASR is the release emissions into the atmosphere. Currently Federal Law requires that all incinerators producing toxic gases in excess one ton/year must have a permit. The toxicity as well as the amount of gas above one ton/year released will relate to how much that permit will cost. Since PVC is used in less than one percent in the production of auto-plastics for the plastic types used, the release of PCDD's and PCDF's is negligible in ASR incineration. These emission types are of the biggest concern by the federal government for the incineration of household plastics.

Other toxic gases are released from certain plastics when incinerated. However, a dual-stage incinerator will dramatically reduce the formation of these toxic gases and encourage complete combustion of the polymer hydrocarbon chains. The addition of the scrubber will further reduce any possible release of a toxic gas molecule that is still present after the second stage of the incinerator.

In conclusion, toxic gas release from these small-scale ASR incinerators with control equipment should be significantly less than the one ton/year limit imposed by the Federal Government before warranting a permit. Presently no laws are in effect requiring the purchase of a permit for the release of carbon dioxide, however, with global warming becoming an issue of global concern, it may be expected that in the future permits may be required for the release of large quantities of carbon dioxide into the atmosphere.

	ASR Incineration
Economic Analysis	64,000 Cars Processed Annually
Calculated Capital Costs	$668,000
Initial Profits Assuming: * = Capital Costs paid off by the 1st year ** = Capital Costs paid off by the 2nd year *** = Capital Costs paid off by the 5th year	* $830,000 Profit
Annual Profits/Loss After Capital Costs are Paid	$1,480,000 Profit
Total Industry Profits including the sale of Steel Scrap and Parts	~$136500000
Most Significant Factor(s) that would Degrade Annual Profits	Increased Clean Air Regulations Decreased Electricity Prices
Environmental Analysis	
Percentage of Automobile Plastics Recycled: * = material recycled for reuse ** = recycled by energy recovery	** 68%
Resulting Pollution Type	Green House Gas Emissions

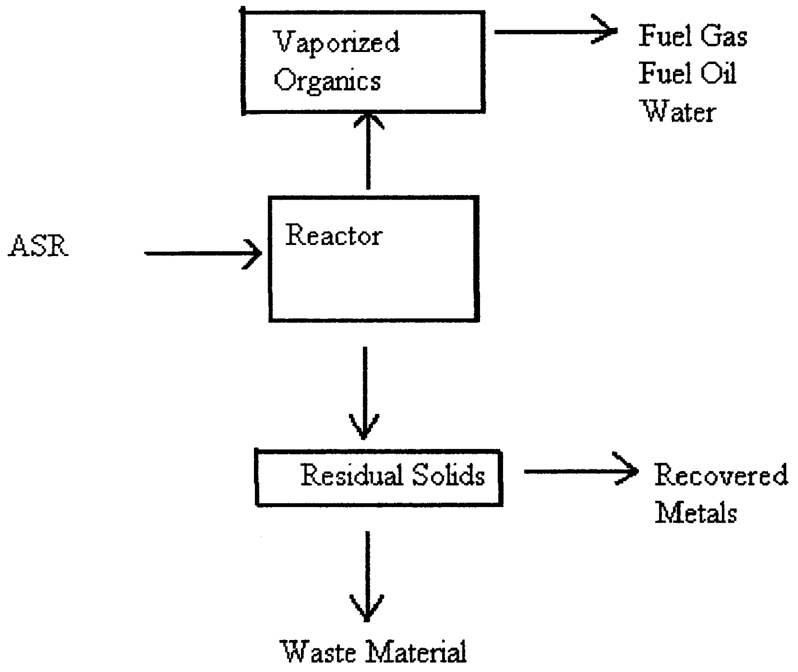
Table 4 - ASR incineration Results

5.4 Pyrolysis

5.4.1 Pyrolysis goals

The goals of pyrolysis are to convert organic material of ASR into fuel gas and fuel oil by using a reactor at low pressures and high temperatures that vaporizes the organic material to a gas and then some of it is condensed to oil. The metals from ASR are then separated from the residual solids and recycled.

5.4.2 Process Flow Diagram



5.4.3 Process Analysis

An evaluation of a pyrolysis plant based on a pilot scale plant has been performed by E.T.P. Technologies [41]. The full-scale plant evaluation was designed for 4000 kg/hr, or 8800 lb./hr of ASR. The reactor operates at a temperature of about 530 C and a pressure of 1.5 kPa. The gas formed is pumped to cooling towers for condensation and gas purification. The gas produced has a high heating value due to its high hydrogen content. The oils produced have a high heating value and low sulfur content. Water is easily separated from the oil by decantation. Treatment of the oils could make it a direct substitute for No. 6 fuel oil.

This process reduces the volume of ASR by a factor of 3.7 times the original feedstock [41]. The products formed are broken down by the following weight percent: 18.3% oils, 8.8% iron, 7.3% metal alloys, 37.5% inorganic materials, 8.4% charcoal, 3.9% gas, and 15.8% water [41]. Variations in the composition of the products are dependent upon the processing conditions.

5.4.4 Economic Analysis

The industrial process was designed for 4000 kg/hr, with a fixed capital investment of about $5 million (US). The assumptions made were that the plant was running 24hrs/day 330 days/year, they were paid $15/ton to take ASR, oil can be sold at $13/bbl, ferrous metals sold at $42/ton, non-ferrous alloys sold at $680/ton, and gas sales at $.075/kg (75% of the price of natural gas). Detailed information on the capital cost, incomes, operating costs, and management costs are given in appendix [#]. It was evaluated that a return on the investment of 17% before tax, and a profit of $27/ton can be realized [41].

In order to compare this method of ASR disposal to the other methods, it has to be re-scaled to process the same amount of ASR. The costs and profit are approximated by linearly correlating the costs and returns with the amount of ASR produced. Since a profit $27/ton can be made, the yearly profit can be calculated to be $27/ton*3tons/hour*24hours/day*365days/year = $710,000 dollars profit/year. A capital investment for a plant with a capacity of 6,000 lb./hr of ASR can be approximated by (6,000/8,800)*5,000,000 = $3,410,000.

The amount of material that must be disposed of was the 37.5% inorganic materials, and 8.4% charcoal produced by the process. If the cost to dispose of this material is the same as for ASR, then a waste disposal cost is ((37.5+8.4)/100)%waste*3ton/hr*24*365days/yr*$12/ton= $140,000/yr.

Energy is recovered in the form of fuel gas and fuel oil that can later be burned. The material contains a potential heating value of ((18.2+3.9)/100)(lbgas+oil/lbASR) 6,000lb/hr*10,000btu/lb=13,260,000Btu/hr, which is comparable to the amount of energy obtained through incineration.

5.4.5 Environmental Analysis

This process recycles about 54 wt% of ASR into new materials. The remaining 46% goes to a landfill. The amount of energy recovered by recycling of gas and oil is comparable to the incineration method. The oil and gas produced by this method must eventually be burned to recover the energy, so the type of emissions generated are similar to incineration.

	ASR Pyrolysis
Economic Analysis	64,000 Cars Processed Annually
Calculated Capital Costs	$3,410,000
Initial Profits Assuming: * = Capital Costs paid off by the 1st year ** = Capital Costs paid off by the 2nd year *** = Capital Costs paid off by the 5th year	*** $0
Annual Profits/Loss After Capital Costs are Paid	$710,000 Profit
Total Industry Profits including the sale of Steel Scrap and Parts	~$135,700,000
Most Significant Factor(s) that would Degrade Annual Profits	Decreased Landfilling Costs Decreased Oil Prices
Environmental Analysis	
Percentage of Automobile Plastics Recycled: * = material recycled for reuse ** = recycled by energy recovery	*100%
Resulting Pollution Type	Green House Gas Emissions once the produced fuel oils are combusted

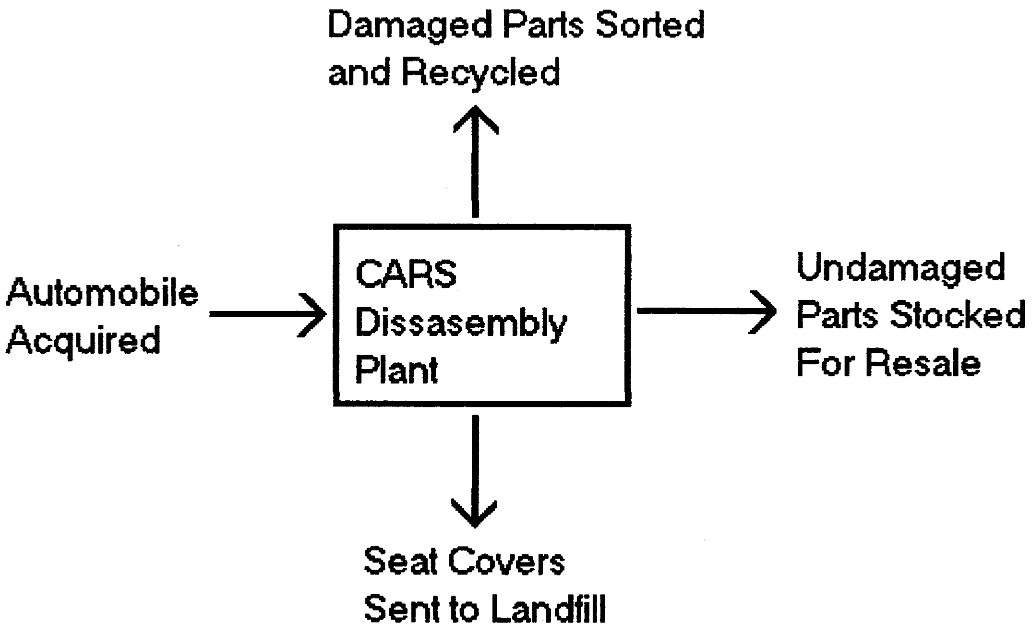
Table 5 - Pyrolysis results

5.5 Automobile Disassembly

5.5.1 Process Goals

The primary goal of automobile disassembly is to remove parts from an automobile and either use them again as is, recondition them, or separate them by material type for recycling purposes. Currently, the majority of automobiles are stripped by auto wreckers of their most valuable parts before being sent to an auto shredder for metal recovery, and the generation of ASR. A new technique, however, is being explored in which an automobile disassembly plant is used to fully disassemble an automobile, and totally eliminate the production of ASR.

5.5.2 Process Flow Diagram



5.5.3 Process Analysis

Automobiles are obtained from auctions, charities, insurance companies and various other private sources. It takes approximately 90 minutes for the crew at CARS to fully disassemble an automobile. Unlike other disassembly methods, CARS uses a reverse assembly-line process to dismantle the automobiles in a very efficient manner. Through this disassembly process, over 99% of the automobile is recycled, excluding the seat covers which are sent to landfills as waste. The common tools used in the disassembly process are wrenches, with the occasional use of saws and torches. Specialized mechanical devices are used to spin, and rotate automobiles so parts are more accessible for removal. Energy costs are low because the gasoline and oils from the automobiles are recycled and converted to electricity in generators at the plant.

5.5.4 Economic Analysis

The total startup costs for a CARS plant is significant, it is estimated to be approximately 20 million dollars. The purchasing price of an automobile for the purpose of disassembly can be found to range anywhere between $100 and $5 [56]. The profit margin for the CARS plant is claimed to be $5.00 for every dollar spent, or a profit of 400%. A CARS plant employs approximately sixty people at an average hourly rate of $14.00 per hour [55]. This calculates to roughly 2.5 million dollars annually in labor costs. Assuming the plant operates 9 hours a day, and it takes 90 minutes to disassemble an automobile [56], it can be calculated that about six cars can be disassembled at the plant per day. Using an average price of $2,500 per automobile and a 365-day workyear, nearly 5.5 million dollars is spent to acquire the automobiles, and 2,200 automobiles are processed annually. The sale of parts from the CARS plant makes approximately 27 million dollars per year. The total annual profit for CARS can be computed using the following equation:

Total Profit = Parts Sales - (Labor Costs + Car Costs + Additional Overhead Costs)

Assuming that overhead costs are negligible since gasoline from the automobiles can be used to help generate electricity, the total profit per year can be computed to be close to 19 million dollars.

5.5.5 Environmental Analysis

About 99.5% of an automobile that goes through a CARS plant is recycled. The only major part of an automobile that is not recycled at a CARS plant is the seat covers. Every other part of the car is recycled in some form. The fluids are drained and used to supplement the costs of heating and generating electricity for the plant. The usable body panels and parts are tagged and separated for sale as replacement parts. The plastics are separated by type and either reused or sent to be recycled. This type of recycling is environmentally friendly; while at the same time dramatically decreasing the amount of material sent to landfills.

	Design for Disassembly
Economic Analysis	50,000 Cars Processed Annually
Calculated Capital Costs	~$6,000,000
Initial Profits Assuming: * = Capital Costs paid off by the 1st year ** = Capital Costs paid off by the 2nd year *** = Capital Costs paid off by the 5th year	*$188,000,000 Profit
Annual Profits/Loss After Capital Costs are Paid	$194,000,000 Profit {it must be noted that these profits include all parts, plastic as well as non-plastic}
Total Industry Profits including the sale of Steel Scrap and Parts	~$194,000,000
Most Significant Factor(s) that would Degrade Annual Profits	Increased Labor Costs Increased Land Costs
Environmental Analysis	
Percentage of Automobile Plastics Recycled: * = material recycled for reuse ** = recycled by energy recovery	*99.5%
Resulting Pollution Type	Negligible

Table 6 - Design for disassembly results

6.0 Conclusions

Through research it was discovered that there are currently four possible methods for the disposal of automobile plastics. Although four different methods exist, only one is widely practiced (landfilling). Previously there has not been enough information available to make a widespread choice as to which method is the most favorable for the car-reclamation industry to invest in. Using information obtained through research and interviews with various experts in the automotive recycling field, economic and environmental issues were compared and used to evaluate when specific methods would be most favorable over one another.

The landfilling of automobile plastics in the form of Automotive Shredder Residue (ASR) has occurred for the last forty years. With the decrease in landfill space and increase in public concern for the environment, landfill-tipping fees for household materials have seen a steady increase over the last ten years. Despite this price increase, ASR has remained relatively inexpensive to dispose of in landfills, and consequently little research has been conducted regarding alternative methods of disposal. With the culmination of increasing landfill costs, increasing plastic content in ASR, and environmental concerns , a reassessment of the situation has become necessary to justify the continued landfilling of ASR as the disposal method of choice. A chart on the next page has been constructed to compare economically and environmentally for the methods analyzed.

Economic and Evironmental Conclusions

	Landfilling ASR	Recycling ASR (calculated at PU and ABS prices of $0.25/lb)	ASR Incineration	ASR Pyrolisis	Design for Disassembly
Economic Analysis	64,000 Cars Processed Annually	64,000 Cars Processed Annually	64,000 Cars Processed Annually	64,000 Cars Processed Annually	50,000 Cars Processed Annually
Calculated Capital Costs	$0 {It should be noted a shredder facility has a capital cost of ~$1.6 million}	PU: $416,000 PU/ABS: $900,000	$668,000	$3,410,000	~$6,000,000
Initial Profits Assuming: * = Capital Costs paid off by the 1st year ** = Capital Costs paid off by the 2nd year *** = Capital Costs paid off by the 5th year	$0	PU: ** $435,000 Loss PU/ABS: ** $100,000 Profit	* $830,000 Profit	*** $0	*$188,000,000 Profit
Annual Profits/Loss After Capital Costs are Paid	$315,000 Loss	PU: $227,000 Loss PU/ABS: $500,000 Profit	$1,480,000 Profit	$710,000 Profit	$194,000,000 Profit {it must be noted that these profits include all parts, plastic as well as non-plastic}
Total Industry Profits including the sale of Steel Scrap and Parts	~$134,600,000	PU: $134,700,000 PU/ABS: $134,500,000	~$136,500,000	~$135,700,000	~$194,000,000
Most Significant Factor(s) that would Degrade Annual Profits	Increased Landfill Costs Increased Trucking Costs	Decreased Oil Prices	Increased Clean Air Regulations Decreased Electricity Prices	Decreased Landfilling Costs Decreased Oil Prices	Increased Labor Costs Increased Land Costs
Environmental Analysis					
Percentage of Automobile Plastics Recycled: * = material recycled for reuse ** = recycled by energy recovery	0%	PU: *5% PU/ABS: *23%	** 68%	*100%	*99.5%
Resulting Pollution Type	Nontoxic Landfill Waste	Toxic Solvent Used in Froth Flotation	Green House Gas Emissions	Green House Gas Emissions once the produced fuel oils are combusted	Negligible

6.1 Landfilling

From the results and calculations made, currently $315,000 is spent annually by an average shredder facility to dispose of their ASR. The most positive implication of this disposal method is that the industry is already established and no additional capital costs are required. The industry is encouraged to continue with this practice by the low costs of landfilling ASR due to its suitably for use as a top-cover material, and since it is considered non-toxic. In addition, a large assembly of individually owned automobile dismantlers across the United States encourage the continuation of this cycle. Before ASR is disposed of, it is calculated that approximately $135 million in profits are generated from the combination of used parts sales and scrap steel sales. Although this method is currently widely accepted, other methods available are economically and environmentally superior, and will most likely become even more so in the future as landfill space decreases and oil prices increase. The profits from parts and scrap steel are much larger than the ASR disposal costs by each of the methods. This results in similar total industry profits.

6.2 ASR Recycling

The least profitable alternative method to landfilling for disposing of automobile plastics was the removal of polyurethane from ASR using a froth-flotation system. It would reduce ASR landfilling fees upon shredders from $315,000 to $227,000 annually, and would require a capital investment of $416,000 to be made. In addition, the chemicals required for the froth foam are toxic and special precautions must be taken when using or disposing of them. The most positive aspect of this method is it could be implemented into the current shredder industry. It should be noted that, although a method is being investigated to incorporate ABS recovery with this PU froth flotation recycling process, the additional profits are small relative to the additional capital costs that would need to be invested. Since there are other recycling methods available that are more productive both economically and environmentally, further research to improve this method will be necessary before this method is used on a large scale.

6.3 Energy Recovery

Another alternative to landfilling ASR is energy recovery through either incineration or pyrolysis. An average ASR incinerator would have a higher average annual gross profit of $1,480,000 annually, and lower capital cost, $668,000, compared to pyrolysis, $710,000 and $3,410,000 respectfully. However, incinerators release emissions, and in some areas where permitting fees are high for the release of these emissions, incineration could be less profitable. In the end, however, both methods are equally as destructive to the environment since the fuel gas and oil formed by pyrolysis are eventually burned, releasing emissions. The only difference is that the pollution is immediate for incineration, while in pyrolysis the fuel generated is sold for later use. The positive aspects of these two methods is that they could be incorporated at currently existing shredder facilities, remove contents from ASR waste, and make use of energy from material that otherwise would be wasted. While both these previous methods seem like sensible solutions that could be easily incorporated into a typical shredder facility, they are still not extremely profitable and the industry is not widely developed.

6.4 Design for Disassembly

The automotive plastic disposal method that was found to have the highest profit and smallest environmental impact is the design-for-disassembly method involving the use of a CARS plant. Although the startup cost of ~$6,000,000 is high in comparison to the other methods, the annual net profit would be ~$194,000,000. Using this method, very little automobile plastics would be sent to landfills. All plastic parts from the automobile with the exception of scraped seat covers are either stocked for resale or sorted by their respective plastic type and recycled. Because of the staggering economic and environmental advantages this method over the others investigated, it was interesting to find why is method has not yet found more support. Although there are many contributing factors, from our investigation and comparison to European practices, it appears that the primary reasons are due to legislation and lack of government regulation in this area of industry. European standards in the disassembly for end-of-life-vehicles industry took their initial steps only after being threatened by government action in the form of increased taxation by the governments if steps were not taken to reduce the amount of automobile waste going to landfills. In the U.S. it appears that despite the obvious economic and environmental benefit a CARS disassembly plant has, the current automotive disposal industry has a strong foothold and the industry is resistant to change.

The results of this project, show that despite the more productive economic alternatives available, a large amount of effort will be needed to change the common disposal practice of selling parts from end-of-life vehicles, shredding them, and sending the ASR to landfills. It is doubted that in the US that the government will take strong action anytime soon to change the current method. It is hoped that the environmental and economical advantage associated other methods, especially total disassembly, can be realized as a more productive means for the disposal of automobile plastics.

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8.0 Appendix

I. Pyrolysis economic information [41]

II. Summary of weight of material and times for disassembly [59]

8.0 APPENDIX I
from source [41].

Table 9. CAPITAL COST OF A 4000 kg/h PYROLYSIS PLANT (M $ U.S.)

Direct Costs	Equipment	2.10	
	Delivery and installation (50%)	1.05	
	Instrumentation (installed) (13%)	0.27	
	Piping and Insulation (10%)	0.21	
	Installation of electricity	0.21	
	Total direct costs*	3.84	3.84
Indirect Costs	Engineering and management (30%)	0.63	
	Contractor fees	0.31	
	Total indirect costs	0.94	0.94
Cost of the Recovered Metal Treatment Plant (RMTP)			0.25
Fixed capital investment			5.03

* The direct costs do not include the land, the buildings, roads, water and electricity facilities and the wastewater treatment plant.

TABLE 10: FEASIBILITY OF A 4000 kg/h ASR VACUUM PYROLYSIS PLANT (in k$ U.S.)

CAPITAL INVESTMENT		
Plant capacity:	4000 kg/h @ 7920 h/year	5000
INCOMES		
Fees	31680 t/yr @ 15$/t	475
Oil	5797 t/yr @ 13$/barrel	520
Gas	1.235 Mkg/yr @ 0.075 $/kg	93
Recovered Metals:		
	- Fe, 2788 t @ 42$/t	117
	- Cu, 215 t @ 680$/t	146
	- Al, 430 t @ 680$/t	292
	- Zn, 177 t @ 680$/t	120
	- Non ferrous alloys, 1473 t @ 680$/t	1002
OPERATING COSTS		
Electricity, 1200 kW @ 0.04$/kWh		323
Replacement, maintenance (3% of fixed capital)		155
Manpower, 12 workers		340
Wastewater treatment		68
MANAGEMENT		
Depreciation and financial costs (17.5% of capital cost)		875
Miscellaneous expenses and fees, taxes		145
PROFIT (in $/t)		27

VRDC U.S. Field Trial

1988-1994

Tempo & Topaz

Summary of Weights and Times

Material	***Total Contaminated Weight (lbs)* ***	***Total Clean Weight (lbs)* ***	***Total Removal Time (min)* ***	***Total Cleaning Time (min)* ***	***Total Time (min)* ***
PP	42.70	22.86	13.07	9.20	22.27
EPDM	15.60	15.60	0.72	0.00	0.72
Aluminum	19.22	14.94	3.58	5.92	9.50
ABS	9.38	7.95	4.92	1.55	6.47
TEO	3.21	3.13	2.65	1.00	3.65
PA66	1.79	1.54	0.37	0.17	0.54
	91.90 lbs	66.02 lbs	25.31 min	17.84 min	43.15 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time

*These totals do not include the Depollution data

VRDC U.S. Field Trial

1982-1995 Cutlass Ciera & Century

1982-1991 Pontiac 6000

1982-1990 Celebrity

Summary of Weights and Times

Material	***Total Contaminated Weight (lbs)* ***	***Total Clean Weight (lbs)* ***	***Total Removal Time (min)* ***	***Total Cleaning Time (min)* ***	***Total Time (min)* ***
Aluminum	13.89	12.69	10.50	4.05	14.55
ABS	11.25	10.52	6.53	2.60	9.13
PP	9.12	8.09	4.40	0.28	4.68
EPDM 2	7.02	7.02	0.30	0.00	0.30
PA 66	8.05	3.39	1.70	1.45	3.15
TEO	1.56	1.36	0.17	0.03	0.20
EPDM 1	0.74	0.74	0.28	0.00	0.28
PC	0.69	0.44	0.15	0.27	0.42
	52.32 lbs	44.25 lbs	24.03 min	8.68 min	32.71 min
Summary of Wagon Loadspaces Only					
PP	20.77	18.52	1.33	0.52	1.85
EPDM	2.35	2.35	0.08	0.00	0.08
	23.12 lbs	20.87 lbs	1.41 min	0.52 min	1.93 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time

*These totals do not include the Depollution data

VRDC U.S. Field Trial

1981-1990 Ford Escort 4 Door

Summary of Weights and Times

Material	Total Contaminated Weight (lbs) *	Total Clean Weight (lbs) *	Total Removal Time (min) *	Total Cleaning Time (min) *	Total Time (min) *
Aluminum	44.50	34.54	7.62	11.28	18.90
PP	18.88	18.30	9.30	1.03	10.33
PUR	12.56	12.56	3.35	0.00	3.35
EPDM	12.80	12.56	0.32	0.05	0.37
ABS	8.55	8.17	4.37	3.70	8.07
TEO	7.63	7.64	5.53	0.00	5.53
PC	7.20	3.87	4.17	2.58	6.75
	112.12 lbs	97.64 lbs	34.66 min	18.64 min	53.30 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time

*These totals do not include the Depollution data

VRDC U.S. Field Trial

1984-1990

Caravan & Voyager

Summary of Weights and Times

Material	*Total Contaminated Weight (lbs)* *	*Total Clean Weight (lbs)* *	*Total Removal Time (min)* *	*Total Cleaning Time (min)* *	*Total Time (min)* *
ABS	71.43	58.03	16.17	8.57	24.74
Aluminum	30.69	30.69	12.28	0.00	12.28
PUR	19.80	19.80	6.77	0.00	6.77
PP	26.69	18.56	6.73	3.17	9.90
EPDM	15.39	15.39	1.32	0.00	1.32
TEO	4.53	4.53	2.78	0.00	2.78
PA66	2.07	1.93	0.68	2.67	3.35
	170.60 lbs	148.93 lbs	46.73 min	14.41 min	61.14 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time

*These totals do not include the Depollution data

VRDC U.S. Field Trial

1988-1994 Cavalier

4 Door Sedan & Wagon

Summary of Weights and Times

Material	***Total Contaminated Weight (lbs)*** *	***Total Clean Weight (lbs)*** *	***Total Removal Time (min)*** *	***Total Cleaning Time (min)*** *	***Total Time (min)*** *
PUR	21.84	21.84	7.65	0.00	7.65
PP	19.64	17.38	14.05	3.83	17.88
Aluminum	12.03	12.03	4.38	0.00	4.38
ABS	11.12	10.22	3.93	3.60	7.53
EPDM	9.63	9.63	0.33	0.00	0.33
PA 6	2.70	2.70	1.83	0.00	1.83
PC	0.41	0.41	0.67	0.00	0.67
	77.37 lbs	74.21 lbs	32.84 min	7.43 min	40.27 min

1988-1994 Cavalier Wagon - Loadspace Only

PP	13.45	12.79	0.97	0.50	1.47
EPDM	2.41	2.41	0.07	0.00	0.07
	15.86 lbs	15.20 lbs	1.04 min	0.50 min	1.30 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time

*These totals do not include the Depollution data

VRDC U.S. Field Trial

1986-1991 Taurus & Sable

4 Door Sedan & Wagon

Summary of Weights and Times

Material	*Total Contaminated Weight (lbs)* *	*Total Clean Weight (lbs)* *	*Total Removal Time (min)* *	*Total Cleaning Time (min)* *	*Total Time (min)* *
Aluminum	20.50	16.93	7.35	8.50	15.85
TEO	14.45	13.01	1.73	2.55	4.28
PP	13.68	12.80	3.93	0.78	4.71
EPDM	11.94	11.94	0.38	0.00	0.38
ABS	10.61	9.62	1.92	5.68	7.60
PUR	9.14	9.14	6.10	0.00	6.10
PA 66	13.42	8.28	3.23	1.70	4.93
PC	2.00	1.29	0.07	0.33	0.40
Brass	1.00	1.00	0.02	0.00	0.02
	96.74 lbs	84.01 lbs	24.73 min	19.54 min	44.27 min

1986-1991 Taurus and Sable Wagons - Loadspace only

PP	12.64	8.02	0.83	0.67	1.50
ABS	6.74	6.45	1.43	0.42	1.85
TEO	5.50	3.38	0.67	0.43	1.10
EPDM	2.34	2.34	0.05	0.00	0.05
	27.22 lbs	20.19 lbs	2.98 min	1.52 min	4.50 min

Total Contaminated Weight = weight of parts as they were when taken off the vehicle
Total Clean Weight = weight of parts after cleaning
Total Removal Time = time it took to remove from vehicle
Total Cleaning Time = time it took to remove contaminants
Total time = Total Removal Time + Total Cleaning Time