MULTI-LIFECYCLE ASSESSMENT
OF
CATHODE RAY TUBES

by
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A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Manufacturing Systems Engineering

Department of Industrial and Manufacturing Engineering

October 1997

ABSTRACT

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Over the past few years environmental issues and concerns have become more and more important, as they become a common part of most people's personal experience. In these regards, the electronics industry is facing substantial problems in terms of end-of-life management of its products, televisions and monitors in particular. The building blocks of this industry are usually viewed as relatively "clean". However, manufacturing by-products of the electronics industry and the disposition of electronics are becoming increasingly important technical, financial, and environmental issues.

Within the context of the above issues, environmentally responsible disposal of Cathode Ray Tubes (CRT's), which is still the prominent display of choice for both the television and the computer monitor, is regarded as a major concern, due to the high amount of lead in the CRT glass. A considerable proportion of the environmental effects of a CRT is related to its lifecycle and also to the lifecycle of its materials. And hence to analyze and assess the environmental impact of the raw materials used in a CRT during its complete lifecycle, the method of Multi-Lifecycle Assessment (MLCA) is adopted in this research and thesis. A generic process modeling structure for manufacture of materials is developed to conduct a full inventory analysis, in terms of mass balance, energy balance and environmental performance. The demanufacturing aspect of

televisions is also addressed. The disassembly process is studied and different disassembly levels are analyzed using the reverse fishbone diagram technique. Considering three different end-fate objectives for recovering the subassemblies, components, and materials in the television, a cost effectiveness analysis is also performed to compare end-fate objectives and determine the scenario yielding the highest value for disassembling televisions.

The major contributions and results obtained from this research are as follows:

1. A database for eco-profile of commonly used materials namely, steel, aluminum, copper, lead, and leaded-glass, is generated by conducting LCI of these materials.

2. Environmental burden for the lifecycle of CRT from raw materials extraction to production is calculated.

3. The demanufacturing study conducted suggested that, for profitable and economical operation of a disassembly process, the procedure and level of disassembly, the time required for disassembly, and the current market value of recovered materials, are important and dependent on each other. The demanufacturer has to make a trade-off between these issues and thus try to efficiently and effectively manage the entire demanufacturing operation.

APPROVAL PAGE

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CATHODE RAY TUBES

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This thesis is dedicated to my

beloved parents and other family members

ACKNOWLEDGMENT

I would like to express my sincere gratitude to Dr. Reggie Caudill, who not only helped me as my thesis advisor, providing valuable resources, insights and intuition, but also gave me support and encouragement.

Special thanks to Dr. Valerie Thomas and Dr. Sanchoy Das for actively participating in my committee. I take this opportunity to thank Ms. Elizabeth McDonnel and all other staff at the Multi-Lifecycle Engineering Research (MERC) for their continuous support and suggestions from time to time. I must also thank Mr. Julian Kliokis for his kind support and valuable information.

I would like to thank the following people, organizations, and companies for providing valuable data and information over the entire period of my research:

- Mr. Jeff Lowrey, Techneglass
- Mr. David Thompson, Matsushita Electronic Corporation
- Dr. Steven Young, University of Ontario
- Mr. Andrew Wade, Wade Environmental Industries
- The Aluminum Association
- Copper Development Association
- Electronics Processing Association, Inc.
- Hammond Lead Industry

I also thank all those individuals not specifically delineated here who assisted me in this research.

Finally, I thank my friends for their continuous help, support and encouragement.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

Chapter **Page**

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF FIGURES

LIST OF FIGURES
(Continued)

Figure **Page**

CHAPTER 1

INTRODUCTION

1.1 Background

Over the past few years environmental issues and concerns are becoming more and more important, as they become a common part of most people's personal experience – urban smog or radioactive wastes. So, corporations are beginning to incorporate explicit consideration of environmental issues into evaluation of ongoing programs and strategic planning for the future [1].

Engineers and researchers have become profoundly challenged by social and environmental issues and must participate proactively in decision making to assure a sustainable future where environmental responsibility is balanced with economic security. Moreover, organizations of all kinds have become increasingly concerned with achieving and demonstrating sound environmental performance by controlling the impacts of their activities, products and services on the environment, through strategic environmental policies and objectives.

Within the context of the above issues, the electronics industry is facing substantial problems in terms of end-of-life management of its products. Due to explosive growth in the consumer electronic industry, countless electronic products such as televisions, computers, telephones etc. are manufactured today. The electronics and computer industry, including computers, communications, semi-conductors and consumer electronics, is one of the largest manufacturing industries in the U.S. The building blocks of the industry are usually viewed as relatively “clean”. However, manufacturing by-products of the electronics industry and the disposition of electronic products are becoming increasingly important technical, financial and environmental issues [2]. Domestic and international air, water, ground and disposal laws and regulations now affect every step in the lifecycle of electronic products. Thus, regulatory compliance is becoming an important cost consideration in electronic systems manufacturing. A disposal problem is felt by all manufacturing sectors and according to U.S. Environmental Protection Agency (EPA), over 12 billion tons of industrial waste are generated annually in the United States. Over one-third of this amount, 4.2 billion tons is classified as hazardous waste generated in manufacturing. Also, it is estimated that by the year 2005, there will have been approximately 150 million personal computers (PC’s) and workstations sent to landfills [2].

Most of these household electronic products contain a variety of toxic substances (e.g. lead, cadmium, and mercury) at varying levels of concentration and also their design dictates durable and sometimes bulky materials. The disposal of these products into municipal solid waste landfills and incinerators is becoming a matter of increasing concern due to limited landfill capacity. Thus, to address all these issues, problems, and concerns, researchers are working in many different areas of this entire problem of environmentally benign disposal of electronic equipment’s.

A considerable proportion of the environmental effects mentioned above are related to the lifecycle of electronic products and their materials. Environmental impact related to electronic products is closely connected to energy use, emissions of carbon dioxide, carbon monoxide, nitrogen oxides, and especially, lead exposures. However, environmental impacts related to electronic products may also have causes other than energy use when the entire lifecycle of these products is considered. These include process emissions from production of raw materials used for electronic products, waste from production, operation, and disposal of the products. Computers, televisions, and other electronic products and their lifecycle contribute to resource depletion, human health impacts and other environmental impacts. Depletion of resources relates primarily to the use of non-renewable fuels for the production of energy, use of raw materials for the production of electronic products and, in some areas, also to the use of clean ground water and of vacant land.

Hence in the light of above problems, companies and organizations have recognized the need for information about the environmental impacts associated with their electronic products. Some companies have developed "Green" products, for example, Phillip's "Green TV". More stringent requirements are consequently now being made on the environmental soundness of products, and environmental adaptation of products has become an increasingly competitive weapon for the industry. The designers need guidelines to help them to make environmentally acceptable decisions during the designing and production of electronic products. Thus, in order to make an inventory and assessment of the total environmental impact for the complete lifecycle of an electronic product, information and data concerning materials, different components and manufacturing processes are necessary. In these regards Multi-Lifecycle Assessment

(MLCA) proves to be a effective and communicative tool for conducting the lifecycle assessment or analysis of any product.

1.2 Aims and Objectives

The principle aims and objectives of this research are to analyze and assess the environmental impact of the raw materials used in a Cathode Ray Tube (CRT) during its complete lifecycle by using the method of Multi-Lifecycle Assessment (MLCA) as a tool. The objective here is to develop a generic modeling structure for materials manufacture and conduct a full inventory analysis, in terms of mass balance, energy balance, and environmental performance of the raw materials and specifically concentrating on metals such as steel, aluminum, copper, lead and also leaded glass. The other objective of performing the inventory analysis is to calculate the environmental burdens of a CRT from its raw material extraction through production. Another important aim is to study the demanufacturing aspects of televisions, by analyzing their disassembly process and identifying the various end-of-life fate categories of its components and especially for CRT with the help of reverse fishbone diagram. A cost effectiveness analysis is also performed to compare different reverse fishbone diagrams generated for different end-fate objectives of subassemblies and materials. The intention is also to exemplify how the new multi-lifecycle engineering approach may be applied to cathode ray tubes.

1.3 Research Need and Purpose

The cathode ray tube is still the prominent display of choice for both the television and the computer industry. Television dominates the installed display base, both because of size and ubiquity. Computer displays are also becoming pervasive with sales exceeding 17M, making it almost as large as the TV market (25M) in 1994. Also, the Electronics Industries Association (EIA) has estimated that approximately 10M TV sets are destined for disposal in the U.S each year [3].

The main issues associated with the televisions and the monitors are as follows,

- The large volume and weight of the display creates a landfill problem. The size of the display depends upon the face area and size of the cathode ray tube, and therefore the form factor of the display cannot be reduced significantly.
- The lead content of the CRT funnel glass and the neck glass, which has an unknown impact on their final disposal, is of concern. A 1989 Environmental Protection Agencies (EPA) study of products containing lead and cadmium in municipal solid waste estimated that in 1986, 24 percent of all lead in the municipal waste stream was attributable to television picture tubes, second only to lead-acid batteries, which accounted for 65 percent [4].
- Another important concern is the instability and infrastructure issue of a well organized, television and computer demanufacturing industry. This is also a major area of concern because of the fact that the televisions and the monitors are made up of different sizes and materials composition (leaded glass, metals, plastics, etc.) which are not readily biodegradable.

- Other concerns are the toxic emissions and their exposures during mining and production of raw materials needed for televisions and monitors. There are also various emissions during the production of televisions and monitors.

Considering the above problem areas and their importance, there is a definitive need for in depth research in this area of television and monitor lifecycle assessment. The purpose and need then is to consider the lifecycle stages relevant to this area and identify key environmental concerns, during design, production, use, and demanufacturing. There should be a systems approach to environmental cost/impact and current technology efforts, by organizations such as government, industry, and academia. For the purposes of this research and study, the stages of the lifecycle of a television begin with raw material extraction and manufacture and end with disposition, where disposition consists of reuse, remanufacture, reengineer, incinerate, and landfill. The lifecycle approach was chosen for the purpose of the study because lifecycle assessment requires an analysis of environmental impact through design, manufacture, and use to the disposal of the product. Also, similar to traditional lifecycle assessment, a new approach called as Multi-Lifecycle Assessment (MLCA) is suggested. The last section of this chapter discusses this new aspect and the engineering behind this termed, as Multi-Lifecycle Engineering (MLCE).

This thesis in particular addresses the raw material extraction and manufacture of different metals and leaded glass used for the fabrication of CRT's for televisions and monitors, and also studies the disassembly procedure and evaluation of a typical discarded television.

1.4 Research Scope

In today's electronics industry there are a wide variety of products from several different manufacturers. Consequently to provide a meaningful analysis, it is necessary to narrow the scope to a particular product – CRT's. Cathode ray tubes are part of many of these products and are also of concern in terms of their environmental impacts and disposal problems. Hence CRT's were selected for study purpose. For the demanufacturing study a ten year old discarded television was selected, as it is one of the most manufactured domestic and commercial electronic product in terms of numbers.

1.4.1 Selection of Product and its Source:

Due to the vast number of problems associated with electronic products, which have been identified in the earlier sections of this chapter, televisions and monitors were selected as representative of products from the electronics industry. A more detailed analysis was done on cathode ray tubes as they are of major concern in these products. Currently there are significant barriers and few incentives to encourage more demanufacturing of these products, which continue to enter the municipal solid waste stream in increasing numbers. These products were selected as representative of the universe of electronic products due to the major issues, like their ubiquity, large size, and toxic material content, associated with their entire lifecycle. The main toxic material of concern here is the lead used in the CRT glass, which may leach when the CRT glass is landfilled.

1.5 Multi-Lifecycle Engineering

Over the last decade, America's manufacturing industry has struggled to achieve a balance between economic security and environmental responsibility. While individual efforts to reduce process wastes and design green products have been initiated, overall progress has been slow. Due to increasing political and societal pressures, the need to increase the pace for more environmentally friendly products is felt by many companies. Also, regulations and impositions such as the take-back laws in the European Community, require manufacturers to recover and recycle their discarded products. These policies foretell a significant change to an entirely new industrial paradigm which will have profound impact on our Nation's future.

Towards this end, Multi-Lifecycle Engineering (MLCE), a new approach in today's environmental arena, is based on the principle of sustainable economy where competitiveness is balanced with environmental responsibility. Current practices have created a linear flow from raw material extraction and processing into products and packaging which are all too frequently used once and then discarded into landfill. Numerous statistics point out the scope of this problem. It was reported by the National Academy of Sciences that, 94 percent of all natural resources extracted from the earth enter the waste stream within months [5].

Consumer electronics, computers, and household appliances contribute significantly to the environmental burden placed on the municipalities across the nation. If discarded products and waste streams such as these can be recovered and reengineered into valuable feed streams, then we can break this trend and achieve sustainability. For doing this, a new approach is necessary, which takes a systems perspective and considers fully the potential of recovering and reengineering materials and components from one product to create another, not just once, but many times. This is not simply recycling or design for the environment, but rather a complex, next-generation engineered system that transcends traditional discipline boundaries in search of fundamental scientific knowledge, new methodologies and technologies.

Taking all the above issues into consideration, the main thrust of Multi-Lifecycle Engineering (MLCE) is:

- To develop an integrated product and process design system incorporating full multi-lifecycle consequences of the product with particular emphasis on material and form substitution in design, lifecycle assessment, next-generation use, material recovery and value analysis
- To characterize materials from waste streams, reengineered material systems, structure/property relationships, and predictive models for mixtures based on fundamental characterization of component elements
- To focus on separations technologies as a research area that supports material recovery from mixed or contaminated waste streams and the development of clean production processes
- To develop tools and techniques associated with demanufacturing, especially for new fastener technologies, disassembly planning and operation, and part cleaning and reliability testing.

This research and thesis focuses on the multi-lifecycle assessment, including some aspects of demanufacturing, such as disassembly operations and material recovery options, from the broad umbrella of Multi-Lifecycle Engineering.

1.6 Thesis Format

The remainder of the thesis is comprised of six chapters:

Chapter 2 presents the current environmental problems, a brief overview of Lifecycle Assessment (LCA) tools, and, in general, the background information related to this research in the form of literature review.

Chapter 3 describes the sources of data, traditional research and LCA methodology and the new Multi-Lifecycle Assessment (MLCA) technique employed for this research and thesis.

Chapter 4 presents background information on Cathode Ray Tube (CRT) markets, functions, technology, manufacturing, and their environmental dilemma.

Chapter 5 presents the detail inventory analysis of the metals and leaded glass used in televisions and computer monitors. The analysis determines the mass and energy balance across the manufacture of these materials and their environmental burdens.

Chapter 6 deals with the television demanufacturing issue. Described is the detailed disassembly procedure for a television and end-of-life fates identified for its components and materials.

Chapter 7 concludes the thesis by summarizing the results obtained during the research and also suggests recommendations for further improvements and research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Over the past two decades, environmental issues have gained greater public recognition. The general public has become more aware that manufactured products consume large amounts of energy and natural resources and thus affect the quality of environment. These effects occur at all stages of the life-cycle of a product, beginning with raw material acquisition and continuing through material manufacture and product fabrication. They also occur during product use and a variety of waste management options such as landfilling, incineration, recycling.

As public concern has increased, both government and industry have intensified the development and application of methods to identify and reduce the adverse environmental effects of these activities. Lifecycle assessment (LCA) is one way to evaluate the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth. This concept is often referred to as "cradle to grave" assessment.

Multi-Lifecycle Engineering (MLE) is the strategic implementation of a university vision at New Jersey Institute of Technology (NJIT) where government, universities, and industry form a partnership to solve the above problems and thus address societal and industrial needs. The primary responsibility of multi-lifecycle engineering is to turn environmental responsibility into a competitive advantage through, innovative new materials re-engineered from waste streams into valuable feedstock, clean manufacturing technologies that minimize waste and maximize flexibility and responsiveness, and consider next-generation life-cycle considerations in the product design process itself. The following sections describe the current problems in today's environment, towards which multi-lifecycle engineering goals are centered. MLE proposes a new technology which goes well beyond today's life cycle considerations and green products into a new realm of re-engineered materials, process technologies and design methodologies and calls it as Multi-Life Cycle Assessment (MLCA) as compared to traditional LCA. The following sections also identify the need for multi-life cycle assessment of products, processes, and activities right from raw material extraction to the final disposal as compared to traditional life cycle assessment. Consumer electronics, computers, and household appliances contribute significantly to the environmental burden placed on our municipalities across the nation and so is the current research subject of multi-lifecycle engineering.

Although life-cycle assessments promise to be a worthy tool in evaluating the environmental consequences of a product, process or activity, the methodology established is relatively new and will require a great deal of research for further development. Expressing the viewpoint of his and other researchers on LCA's in 1993, Fava stated that, "While the LCA methodology may have a few more years before it is widely and universally accepted, its concept is here today and may be applied to business and organizations as an alternative way of addressing environmental problems." The Society for Environmental Toxicology and Chemistry (SETAC) life cycle assessment technical framework workshop report published in January 1991 outlines the technical basis for life cycle studies. The U.S. Environmental Protection Agency also provides guidance and principles on the specific details involved in the conduct of life cycle studies.

2.2 Pollution Prevention

Pollution prevention has become an environmental mantra of the 1990s. The rhetoric is easy, the practice more difficult. We know it is better to prevent than to remediate, and that in most cases attention to pollution prevention opportunities saves money in the long run. But preventing the generation of waste, environmental releases, and the inefficient use of resources requires the use of a suite of complementary environmental design, management, and policy tools - many of which do not exist as yet! With the passage of the Pollution Prevention Act of 1990, Congress took the first step toward creating a proactive regulatory policy that goes beyond command and control. This change in focus will promote industry partnership with the EPA to identify the most efficient approach to environmental problems and maximize the amount of environmental protection obtained for every dollar spent by industry to comply with U.S. environmental policies. Thus for industry, source reduction often means increased efficiency and savings and for the EPA, it means more compliance and less pollution. The EPA concludes that "current environmental regulations must be modified, preferably through a comprehensive, systems approach designed to encourage resource recovery while controlling environmental risks."

2.3 Need for Energy and Material Resource Consumption

The natural resources are consumed at an alarming rate, inspite of the fact that most of them are limited. The amount of fossil fuel that humans expend in one year takes nature roughly a million years to produce, and the extraction rate has been increasing. Figure 2.1 depicts the world energy consumption per capita from 1950 to 1985. At the present rate of consumption, it is estimated that the world has approximately a 30-year oil supply, 25-year supply of natural gas and a 500-year supply of coal [6]. Limitation is not the only problem of energy resources, the production of energy has also been causing problems. No energy technology is completely environmentally benign [7]. Energy consumption dumps more than five billion tons of carbon into the atmosphere each year.

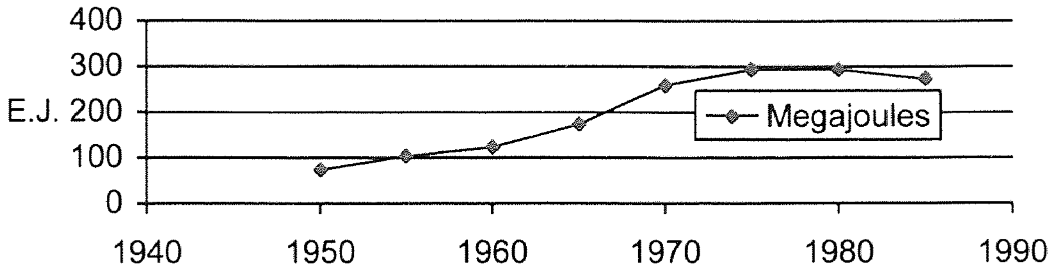


Figure 2.1 World Energy Consumption Per Person (1950-1985)
[Source: 8]

The U.S. EPA found that power used for office equipment rose from 25 million kilowatt hours per year nationwide to 125 million kilowatt hours from the 1980s to the 1990s. Forty percent of the 30 to 35 million computers used in the U.S. are left running overnight and on weekends, when they can be set to the so-called sleeping mode to save energy. In response, the U.S. EPA formalized its Energy Star Computer Program in 1993. New computers should not draw more than 30 watts of power when not being actively used and new monitors should draw less than 30 watts when the PC is idle.

Modern industry is taking material from the earth in a harmful fashion. The U.S. economy is one of the most material intensive economies in the world and extracts more than 10 tons of "active" material per person from U.S. territories, per year. It is estimated that, only 6 percent of this material is embodied in durable goods; remaining 94 percent is converted into waste within a few months of being extracted [8]. It has been indicated that recycling of material should be achieved to reduce environmental impacts caused by resource extraction.

2.4 Solid Waste Management: A Major Problem!

Wastes are generated practically in every industry in one way or the other. The amount of waste generated is enormous and has attracted lot of attention. Waste disposal nowadays no longer proves to be cheap or easy, and the true social costs of disposed material are becoming increasingly apparent. The most visible impact of waste emission is perhaps municipal solid waste (MSW). Comparative data on national solid waste generation are shown in Table 2.1. It indicates that 13.4% of global population generates approximately 290 million tonnes of waste each year. For instance, U.S. households and commercial establishments generate about 4.5 pounds of trash per person each day. Waste produced by U.S. industry during raw material extraction, material processing and product manufacturing is somehow less visible but potentially more serious. Industry generates approximately 700 million tons of hazardous waste and some 11 billion tons of non-hazardous solid waste each year. Figure 2.2 shows that the manufacturing industry has the most responsibility for the total solid waste in the U.S.A. (about 11.7 billions). The National Academy of Sciences reported that 94 percent of all natural resources extracted from the earth enter the waste stream within months [5]. To meet the new environmental regulations, industry can no longer rely upon end-of-pipe solutions, which are not focused on minimizing environmental burdens. Landfilling and incineration, which are considered as acceptable waste management methods today, may cease to help by the time solutions are figured. The solid waste management hierarchy is often cited as a means of justifying the desire to process solid waste by any means other than landfill.

Solid waste management hierarchy:

- waste minimization at source
- re-use
- recycle
- incineration with energy recovery
- incineration without energy recovery
- landfill

This hierarchy places alternative waste treatment options in a fixed order of preference with waste minimization at source as the most environmentally preferred (least environmental impact) option and landfill as the least environmentally preferred (most environmental impact) option. Whilst the solid waste management hierarchy serves a useful purpose, many have come to argue that the hierarchy should not be viewed as fixed and that one should exercise a degree of caution before coming to any immediate conclusions as to what represents the most environmentally preferred solid waste disposal practice. To this end MERC strives to consider fully the potential of recovering and re-engineering materials and components from one product to create another, and not just once but many times. In the rest of the section, the environmental impacts by these material retirement policies will be briefly discussed to illustrate the importance of recycling.

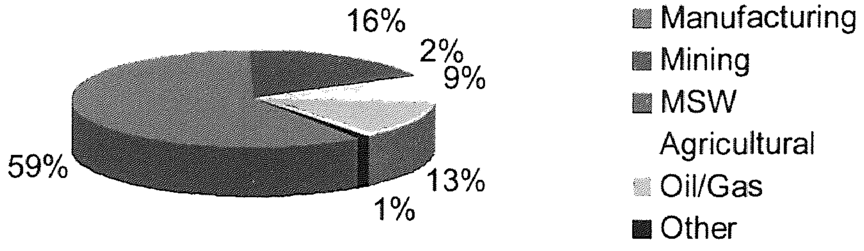


Figure 2.2 Distribution of Non-hazardous Solid Wastes in the U.S.A. (1990)
[Source: 8]

Table 2.1 Comparative Data on National Solid Waste Generation
[Source: 8]

National Solid Waste Generation		
Country	**Total Annual Waste Generation [1,000 tonnes]**	**Annual Per Capita Waste Generation [kgs]**
Australia	8,230	681
Austria	1,341	216
Canada	13,167	642
Costa Rica	440	211
Denmark	1,684	399
Finland	998	247
France	11,523	260
Germany	22,670	447
Greece	2,058	259
Hungary	5,761	658
Ireland	1,045	359
Israel	1,152	330
Italy	11,556	249
Japan	12,960	342
Korea	12,960	679
Netherlands	5,960	500

Table 2.1(Cont.) Comparative Data on National Solid Waste Generation

New Zealand	1,258	5571
Norway	1,340	280
Portugal	1,848	233
Spain	8,724	275
Sweden	2,057	301
Switzerland	1,7666	336
United Kingdom	13,496	291
United States	146,503	744
Total	290,487	

2.4.1 Landfilling

The best site for a landfill is generally one with a natural clay base, which will aid in the prevention of groundwater combination. After a landfill is filled to capacity, it is "capped" with a thick layer of soil. If properly designed and managed, the landfill can then be reclaimed for recreational purposes. There are three general types of landfilling techniques: area fill, trench fill, and modified area fill.

Area fill:

In the area fill method of landfilling, a surface area of ground is prepared for storing wastes. Garbage is then pushed and compacted by a bulldozer in layers about 40 to 70 cm thick. When the thickness of the compacted waste reaches about three meters, roughly 15 cm of cover material, usually soil, is put on the top. The process continues until the landfill reaches its approved height.

The area fill method requires large surfaces of land with moderate and rolling terrain. However, it can handle large volumes of garbage, which must be densely compacted to maximize the amount of space available. The drawbacks of the method is that it takes up large areas of land and requires expensive cover material which may have to be brought in from elsewhere, apart from being costly.

Trench fill:

In this landfilling technique, waste is spread and compacted in an excavated trench below ground level. A trench can be up to 9 m deep and 30 m wide. It can be continuously expanded in length as far as space permits. Garbage is deposited in the trench and compacted into layers by a bulldozer inside the trench until the desired height is reached. Then the compacted garbage is covered with soil excavated from the trench or elsewhere. This method is mostly suitable for the disposal of small volumes of garbage. It accounts for less gas and leachate production per tonne of waste than other methods. Another advantage is that a trench landfill is not as high as an area landfill. Nevertheless, disadvantage of it is that space is used less efficiently than with an area method due to the need for land to separate the trenches.

Modified area fill:

In a modified area landfill, a single row of waste cells (a waste cell is a completed fill section with the cover material) may be excavated below ground level. Garbage trucks enter into the waste cell and tip the garbage along a moderately sloped back wall of the excavated cell. Then, waste is compacted in an uphill fashion into the back wall. Like the trench fill method, it is generally used for landfills intended to be below ground level. The disadvantage of this technique is that it has higher capital costs and tends to produce more leachate and gas than the trench method.

On the whole, there are five main environmental problems associated with landfill operations: gases, nuisance, loss of farmland, and leachate. First of all, contaminated runoff, called leachate, is created in all landfills. It is the liquid, which results when rain or melting snow percolates through waste and carries with it the dissolved materials that it has picked up. It may contaminate groundwater or surface water. The organic matter contained in the leachate can speed up the natural aging of lakes and seas. Also, it can contain many toxic substances, such as heavy metals. The second problem associated with landfill operations is gasses. As landfill waste decomposes, gases such as methane, carbon dioxide and hydrogen sulfide are created. It can also contain toxic substances such as hydrogen sulfide, benzene and vinyl chloride. Most importantly, the production of gas can continue for centuries.

Nuisance is the next environmental concern raised by landfill sites. Nuisance factors include gulls, vermin, odor, and blowing litter. However, these can be reduced by frequently covering the sites with soil and by screening the area to catch trash. The last main problem is the loss of farmland, as many of the best locations for landfills are often on prime agricultural lands. Despite the loss of farmland, there may also be a negative impact on the surrounding water source and the farming community. Yet, with proper site design, operation and closure, it is feasible to return sites to certain agricultural uses.

2.4.2 Incineration

Modern incinerators are highly complex machines. The heart of any incinerator is the combustion chamber in which waste is burned. All waste that enters an incinerator's combustion chamber exits in one of these four forms: combustion gases, particulate material, fly ash and bottom ash. Combustion gasses exit via the stack, although some may be removed by air pollution control devices. Particulate material is comprised of lightweight particles that are borne out of the combustion chamber along with the combustion gasses, but heavy enough to fall out as the gasses cool before leaving the stack, or large enough to be captured by the air pollution control devices. Bottom ash is the solid material that passes through the combustion chamber on the grates, and is usually automatically conveyed to a water-filled pit for quenching. Depending upon the composition of the waste that is burned, incineration can reduce the volume of waste by 70 to 90 percent.

There are a few MSW incinerators, which are currently in use. The most commonly used, and frequently the largest, are mass-burn facilities, which are designed for burning MSW. Modular incinerators are usually smaller-scale facilities that also burn unprocessed MSW. Refuse-derived fuel (RDF) incinerators typically burn shredded waste, from which heavier, non-combustible items such as glass and metal have been removed. Nowadays, most incinerators are equipped with an energy-recovery system.

This is used to capture the heat released during combustion and convert it to steam or electricity. It then serves as a source of revenue to partially offset the costs of the incinerator. Furthermore, modern incinerators must include an air pollution control device. A particulate control device has become a standard accouterment for incinerators.

The newest generation of facilities also has acid-gas scrubbers to remove hydrochloric acid and sulfur dioxide. The obvious and primary advantage of incineration as a waste management method is that it can tremendously reduce the volume of required disposal. One of the major disadvantages of incineration is that emissions from incineration contain cancer-causing substances, such as mercury, dioxins and ash. Moreover, liquid waste streams can be produced by incinerators. Boilers and scrubbers may generate contaminated liquid effluents that are discharged with or without previous treatment. Quench water which is used to cool the ash as it exits the furnace may contain very high levels of salt and heavy metals dissolved from the ash. However, proper design and operation of quench systems can possibly reduce or eliminate the need to discharge these wastes. Despite the negative effects of incineration, converting waste to energy is still cleaner and conserves resources better than landfilling.

2.5 Material Recovery - A Logical Approach to Reduce Environmental Burdens

Normally after the product and its packaging have been used by a consumer and the product has fulfilled its intended purpose, it is either recycled, composted, or discarded as waste. Recycling begins when a discarded product or package is delivered to a collection system for recycling. Composting is the controlled, biological decomposition of organic materials into a relatively stable humus-like material. Recycling decreases the amount of solid waste entering landfills and reduces the production requirements of virgin or raw materials. Two recycling systems for e.g. - closed-loop systems and open-loop systems are considered in the life cycle inventory. Recycling helps preserve our natural resources, especially the non-renewable and limited resources. By recycling, landfill space can be saved for agriculture or wilderness areas. Recycling also saves energy and reduces the airborne and water borne pollution that arises from incineration. In most cases like steel and aluminum it costs less to recycle products than to make new products from virgin materials. Recycling also offers an acceptable alternative to landfilling or incinerating of used products and materials. The remainder of this section discusses three possible material recovery approaches. These recycling streams, which have been identified and used, refer to different aspects of recycling. Aspects of each one of the recycling approaches are addressed as follows.

2.5.1 Reuse

Reuse is the additional use of an item after it has been retired from a clearly defined duty. Reformulation is not reuse. However, repair, cleaning, or refurbishing to maintain integrity may be done in transition from one use to the next. When applied to products, reuse is purely a comparative term. Products with no single-use analogs are considered to be in service until discarded [9]. Reuse retains the highest value of the product and so products should be designed such that its components can be reused.

According to the above definition, "reuse" allows product material to extend its life by reentering the production stage and be reused. Reuse of materials, parts, components or even products is often considered to be the most efficient recycling path among all.

2.5.2 Remanufacture

Remanufacture is an industrial process that restores worn products to a like-new condition. In a factory, a retired product is completely disassembled. Its reusable parts are then cleaned, refurbished, and put into inventory. Finally a new product is reassembled from both old and new parts, creating a unit equal in performance and expected life to the original or a currently available alternative. In contrast, a repaired or a rebuilt product usually retains its identity, and only those parts that have failed or are badly worn are replaced [9].

Remanufacturer is the role that most manufacturers have to play in recycling, aside from fabricating products with recycled material. Remanufacturing involves the fabrication of a product with a mix of new materials or components, and parts or components that are retained and dismantled from post-consumer products (which includes those that are obsolete, returned and discarded).

2.5.3 Reengineering

Reengineering is the reformation or recycling of a recovered material. Reengineering may be defined as the series of activities, including collection, separation, and processing, by which products or other materials are recovered from or otherwise diverted from the solid waste stream for use in the form of raw materials in the manufacture of new products other than fuel. Thus, reengineering is a new technology proposed by MERC and is striving to make good use of the solid waste streams to recover materials from it.

Materials that can be reengineered are generally categorized into two classes, pre-consumer and post-consumer materials. Pre-consumer materials are overrun, off-spec and scrap items generated during the production of a product. Post-consumer materials are materials from goods that have been used, discarded, collected and perhaps shredded. Reengineering involves the characterization of waster streams and development of a fundamental scientific understanding of the performance/processing characteristics and reformulation of materials derived from these streams. If a materials property database is generated then it will provide a link between user requirements and potential feed streams for application development. The data will also provide the foundation for both design synthesis and engineering analysis embodied in the design thrust.

The Office of Technology Assessment in the U.S.A. made a statement about the limitation of recycling based on the results of an assessment of available recycling technology in 1992: "Internationally, 80 percent recycling rates for any material are rare, even in a highly motivated neighborhood. But, there are some exceptions too, such as the lead acid batteries, which have recycling rate of more than 80%. These results indicated that 100 percent material recycle is unlikely with present recycling systems. In fact, it has been suggested that for each recycling system, 100 percent of recycling often does not yield the least amount of negative environmental impacts. This is due to the extra effort required to gather every single unit of the material for recycling. Yet, recycling of certain materials such as old newspapers may lead to a breakthrough in recycling [10]. The amount of newspapers recycled annually by U.S. papermakers from 1981 to 1992 are illustrated in Figure 2.3, which shows a steady increase of both recovery amount and recovery rate. In figure 2.3 the bars indicate the recovery of newspapers in million tons and the line indicates the recovery rate in terms of percentage.

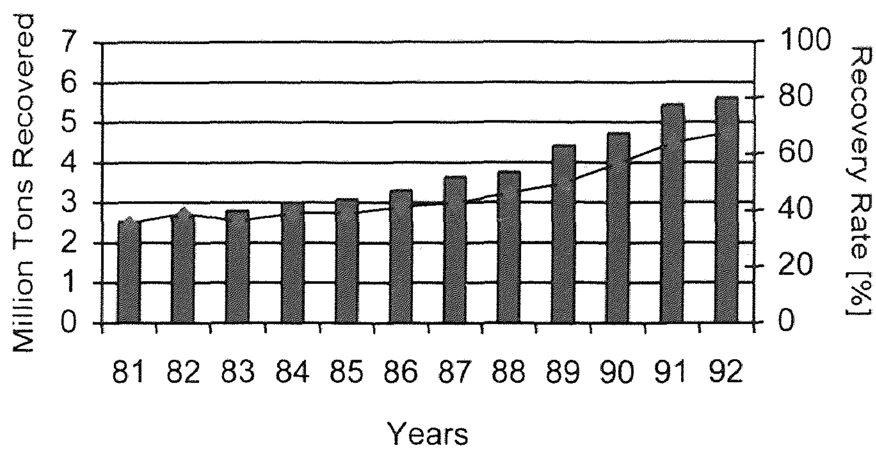


Figure 2.3 Recovery of Old Newspapers in the U.S.A.
[Source: 8]

2.6 Legislation and Regulatory Trends

Over the last ten years, environmental regulations have grown significantly. The computer and electronics industry, as well as many other industries are directly affected by these regulations. Realistically, "Environmental ethics" may not be a good driving-force as regulations and/or economic guidelines. This section will discuss the primary initiation of environmentally conscious production and the secondary driving-force will be discussed in the following section. A unique body of product-related environmental law that extends beyond traditional areas of pollution control is being built up in nearly all European countries. A strong positive correlation between national wealth and environmental consciousness exists in Europe; countries in the forefront include Germany, the Netherlands, Norway, Sweden, Finland and Denmark.

Germany is particularly active in environmental product policy. In May 1991, the Waste and Packaging Law, a part of the Duales System Deutschland Program (DSD Program) was enacted, which states that German manufacturers and retailers from 600 industrial groups have to comply with strict recycling laws. They are now responsible for recovering and recycling their own packaging wastes [8]. This forces manufacturers to account for the product material and solid waste implications of packaging. Germany is also considering similar laws that would make manufacturers responsible for collecting and recycling durable goods, such as household appliances [8]. In England, the government has developed a recycling program which is called the Valpak Program, and its goal is to achieve a reduction of 50 to 70 percent of packaging material by the year of 2000. Moreover, under the UK Environmental Protection Act, it is expected a 50 percent overall recovery of recyclable waste can be achieved by the year 2000 [8]. According to the Recycling Council of Ontario, new packaging legislations have also been introduced by other European governments. In Sweden, all aluminum cans bear a 0.25 Skr (appx. US$ 0.035) deposit. There are packaging taxes on non-refillable beverage containers in Norway and Finland of 1.25 Nkr (appx. US$ 0.19) per liter and FIM 3 (appx. US$0.65). Recently, Japan has invested large sums of money in green product research and development, even though her interest in these areas had lagged somewhat behind that of Europe and the U.S.A. One motivation for Japanese environmental policy is an acute landfill space crisis. In response, the government passed a law in April 1991 that promotes waste recycling. It is expected that around 60 percent of discarded materials including glass, paper, aluminum cans, steel cans and batteries will be recovered by the mid-1990s [8]. The U.S. Congress has passed environmental laws such as the Clean Air

Act, the Clean Water Act and the Resource Conservation and Recovery Act, which raise the cost for industry to release wastes to the air, water and land. Seventeen states out of thirty-eight involved in the promotion of recycling (by buying and using recycled products) offer tax incentives to boost recycling. The U.S. government is encouraging companies to design products that are green [8]. But, these regulations result in tremendous costs.

2.7 Economic and Technological Trends

Besides laws and regulations, economic benefits and technological development make up the secondary force that drives recycling activities. A recent survey of the world market for environmental protection and waste management products and services by ECOTEC estimated that the global market would be worth US$400 billion by the year 2000, compared to US$236 billion in 1992, and equivalent to a real growth rate of almost seven percent. The growth of the recycling market partially comes from the trend that about one-third of all consumers now take ecological concerns into account when making household purchases [8]. The economic power of the "Green-Consumers" intensifies the evolution of environmentally conscious manufacturing and the activities associated with it. Technology acts like a backbone to the production system. No production system can survive without the technology behind it, nor can any recycling system. New technology developed for collection systems definitely helps increase the accessibility of recyclables by recyclers. The amount of recyclables in the waste system can be specifically categorized, as wastes are collected and sorted.

As an example of newer technologies, concrete and windshields, which used to be non-recyclables, are now being recycled. In addition, higher energy-efficiency recycling processes are also being developed and implemented. In the U.S.A., most of the steel that is manufactured is from secondary sources such as automobiles, and aerosol cans. In Canada, in 1994, 68,000 tonnes of steel cans were returned to the steelmaking process to make new steel products; they account for more than 15 percent of high-grade recycled steel.

New technology for recycling plastics has become one of the youngest and fastest growing areas of industry. According to Laidlaw Waste Systems, Hamilton, Ontario, collected empty pop bottles (and similar containers) can now be washed, shredded, melted and spun into plastic fibers. Carpet made of this recycled material is much friendlier to the environment. Other wastes such as old paint and medical waste are able to be recycled and used in the production of recycled products as more advanced recycling technologies are developed. On the whole, the benefits of recycling are threefold: recyclable materials are diverted from landfills; needed scrap materials are more readily available to the steel industry; and taxpayer costs are reduced by eliminating recyclable materials from unnecessary inclusion in household waste collection.

2.8 Life Cycle Assessment (LCA)

Life-cycle assessment is a tool to evaluate the environmental consequences of a product or activity holistically, across its entire life. A complete life-cycle assessment consists of three complementary components: inventory, impact, and improvement analysis. The whole LCA approach and the methodology are mentioned in a separate chapter. This section deals with issues such as applications, benefits, problems and potential solutions, and trends of LCA's.

2.8.1 Production Integration by LCAs

In 1993, Wang *et al.*[11] pointed out that Design for the Environment is a rather proactive approach to investigate and solve environmental problems caused by a product. Design parameters concerned by their methodology include process design, material design and energy consumption. It is mentioned that material flow analysis should be used as a product design tool to aid the design team in assessing the environmental impacts of a design when practicing Design for the Environment. Vigon [12] has proposed to incorporating the life-cycle assessment concept into product improvement, although he finds the procedures for conducting an improvements assessment and the relationships between this component and the others have not yet been fully developed. The baseline life-cycle inventory is expected to be useful in judging what those areas should be that have the most potential to reduce the resource use and environmental burdens.

2.8.2 LCA Applications

Even though the LCA methodology has not matured yet, some organizations including governmental departments, research institutes and companies from industrial sectors see the potential functions and/or requirement of LCA in the future and have actively applied LCAs.

For example, Scott Ltd., a paper manufacturer in East Grinstead, U.K., used a LCA inventory to grade its pulp supplies in 1993. Using a 12-page questionnaire, Scott asked suppliers for data on material and energy consumption and waste emissions. Results showed greater variances among suppliers using the same pulping processes. Based on the analysis, Scott dropped four suppliers who were in the bottom 10 percent. Suppliers could still benefit by being able to see where they stood in relation to their competitors.

The Winnipeg Packaging Project, (WP2) has been organized at "The University of Winnipeg", by Professor Robert Fenton. Its goal is to analyze the environmental impact of packaging alternatives available to Manitoba consumers. There have been three projects done so far, concerning coffee cups, grocery bags and egg cartons separately. In the next project, milk containers will be considered. In the project concerning coffee cups, different types of coffee cups including glass, rigid polystyrene (PS) plastic, paper and foamed polystyrene were compared. It was found that the PS rigid cup could give the lowest energy intensity per serving. On the other hand, in the project which concerns egg cartons, it was found that the plastic carton is less energy intensive than the paper carton [13].

Life-cycle assessment can be applied in both production-oriented and service-oriented organizations. For example, McDonald's Restaurants, which provide fast-food services, have been following the environmental regulations under the 3R's Program. They have successfully obtained detailed information about the volume and types of waste materials being produced in their restaurants. The results of the waste audits, which are conducted with the help of professional environmental researchers and analysts, are now used to evaluate the performance of their outlets and identify new ways of reducing waste. Life-cycle assessment can also help organizations such as hospitals, hotels, offices and construction sites to address the environmental impacts of the services they provide and suggest improvement scenarios. Table 2.2 provides a list of major publicly discussed life cycle analyses.

Table 2.2 Life-Cycle Assessment in the United States
[Source: 14]

Client	**Practitioner**	**Product**	**Year**
Coca-Cola	MRI	Beverage Containers	1969
EPA	MRI	Beverage Containers	1974
SPI	MRI	Plastics	1974
Unknown	MRI	Beer Containers	1974
Goodyear	Franklin	Soft Drink Containers	1978
Proctor and Gamble	Franklin	Laundary Detergent Packaging	1988
Proctor and Gamble	Franklin	Surfactants	1989
Unknown	Franklin	Soft Drink Delivery Systems	
Council for Solid Waste Solutions	Franklin	Foamed Polystyrene and Bleached Paperboard	1990
American Paper Institute	Franklin	Cloth and Disposal Diapers	1990
Council for Solid Waste Solutions	Franklin	Grocery Sacks	1990

Table 2.2 (Cont.) Life-Cycle Assessment in the United States
[Source: 14]

Client	**Practitioner**	**Product**	**Year**
Vinyl Institute	Chem Systems	Vinyl Packaging	1991
National Association of Diaper Service	Lehrberger and Jones	Diapers	1991
Council of State Governments	Tellus	Packaging	1991
Proctor and Gamble	Franklin	Hard Surface Cleaners	1992
Proctor and Gamble	A.D. Little	Cloth and Disposal Diapers	1990

2.8.3 Benefits of LCA's

Some of the benefits of LCA's are not so exciting because LCA methodologies have not yet fully matured or have been widely applied. More unseen benefits may emerge as further development is done and better formulated analyses are performed. Major benefits of LCA's that have been identified by researchers are summarized below:

- Corporations can quantify and assess their product's impact on the environment, to identify opportunities to minimize that impact and save costs by making effective use of available resources.
- More informed decision-making by industry, the public and government relative to the environmental impact of products;

- Better communication and education on the impacts of products based on the more credible and comprehensive information.
- It will prove to be an effective tool for benchmarking environmental performance of a product and can also be used to compare two similar products.

2.8.4 Problems and Potential Solutions of LCAs

The potential problems of LCAs have made their applicability very contentious. Firstly, LCAs are not cost effective for most of the organizations interested in applying them. This is because a holistic LCA is a very data-intensive and time-consuming procedure. The more comprehensive a LCA is, the more time-consuming and expensive it will be. Furthermore, the payback of LCAs and related-research is considered to be long-term and cloudy. In fact, high costs are partly caused by the need for professional consultation and expert knowledge in the impact and improvement analyses. Updating an existing LCA is also costly and time-consuming. Thus, LCAs are expected to be cost effective, timely and easy to update before they will become affordable to most users.

Next, the LCA methodology needs to be standardized. The problem encountered in public policy decisions has three parts. First, system inputs and outputs are measured by different units. Second, there is no unique unit by which costs and benefits can be converted into impact analysis. In other words, weighting factors of environmental and social influences should be able to show relevant impacts. But, any general weighting factors of this type are by necessity highly subjective and without scientific validity. Finally, the means of calculating the impact on the environment and comparing different impacts are by no means standardized [15]. Most approaches to standardization of LCA measurements attempt to convert all different variables to dollar values.

However, most researchers agree that placing dollar values on certain environmental elements such as air, water, fishes and even some natural resources is extremely complicated and subjective, and can be very ambiguous to data users. Huettner proposed that "energy" should be used as the physical measure of environmental and social impacts, of material, capital, and manpower requirements and of reserve quantities to reduce the need to compare or add environmental components with various measurement units [16]. On the other hand, a computer-based tool, called the Environmental Priorities Strategies (EPS) is being developed and will support the conducting of the inventory analysis. Environmental impacts to be assessed are valued on a relative scale according to the "willingness to pay" for avoiding negative consequences. Most controversy about recycling claims arises from lack of consensus about what to include under LCA and the lack of scientifically certain data about impacts.

Thus, data accuracy can in fact be seen as the root of the last two problems. The means of choosing the data used for calculating the impact on the environment and comparing different impacts are not standardized. For example, six Scandinavian studies which utilized LCAs to evaluate the environmental impacts by milk containers have all generated different results and come to different conclusions [15]. Thus, data used in LCAs must be accurate, complete, reliable and verifiable by a third party. Sources of these data should be identified while weighting should be explained. The obstacle, of course, is how analysis data should be gained, analyzed and accessed by users. Solutions to this obstacle are being actively considered around the world. In Europe, the European

Union has selected Denmark as the host country for its Environment Agency, a new institution which will be responsible for collecting and monitoring environmental data collected in all EU member-countries [17]. In Canada, the Canadian Raw Materials Data Base Steering Committee, a sub-group of the Canadian Standards Association (CSA) is establishing the "Canadian Raw Material LCI Database" and will ensure that middle and small-sized companies that cannot obtain their own data can access up-to-date and high quality LCI data. These data will be expected to be consistent, representative, timely and reliable.

Materials now being analyzed include aluminum, glass, paper, plastics and other commonly used industrial materials. The basis of the database is expected to be available to the public and its growth will continue as it is expanded and updated afterwards. One such database is the *BUWAL 250.* In fact, the types of data to be collected will depend on the purpose and scope of the LCA, the reasons for undertaking the LCA and the resources available for conducting the analysis. The purpose of the LCA will determine whether to consider only an inventory of inputs and outputs of the production of a product, or environmental impacts as well. The scope of the LCA will affect how inputs and outputs should be dealt with.

2.8.5 Trends of LCAs

The LCAs' development trend is towards the consolidation of the baseline elements while the objective is still to devise a methodology for meticulous and irrefutable analysis of products. This is because LCAs' requirement of a long-term commitment to reduction of environmental impacts can enhance product and process improvement. Findlay's statement in 1992: "The work carried out in developing the Standard LCA methodology should not be put aside even though some alternative approaches are being considered and generated", indicates that a balanced development between the standard LCA and other alternate approaches is needed. The primary discussions of the LCA development work have revolved around:

- Boundary definitions;
- Identification of assumptions;
- Data requirements and validity;
- Structure of inventory analysis
- Screening methodologies;
- Bridging the gaps between inventory and other assessment components;
- Weighting of impacts;
- Allocation of co-product impacts; and
- Review processes.

Many groups around the world have been working towards the objective. In Europe, LCA is already a prerequisite for products seeking the EC's Ecolabel (880/92/EC) from March 1993. Criteria for washing machines, paints and varnishes have been established, while criteria for 16 other product groups are now being prepared. The International Standards Organization (ISO) is engaged in a project under its Environmental Management Committee, TC207, to develop an international standard for carrying out LCA. The new standard will be incorporated with the Environmental Series (ISO14000) and the Quality Series (ISO9000) in which ISO9004-2 is a guideline for service industries and is the category which most recyclers fall under [18]. On the other hand, Strategic Advisory Group on the Environment (SAGE; Geneva) a subgroup of ISO, is working to make life cycle assessments part of certification programs [19]. SETAC in the U.S. and Europe are forging ahead with the current methodology and framework and holding workshops on an annual basis. Their effort emphasizes the linking of impact analysis to the baseline elements [20]. In Canada, the Canadian Standards Association (CSA) has followed the SETAC, by developing a methodology which is excepted to be published as a Canadian standard [14].

2.8.6 Lifecycle Assessment Software

Computer-based tools have been used for determining more important areas, in terms of environmental impacts, (e.g. CO2, scrap steel, scrap foamed plastics) from the initial set of options. Most of these tools need to be modified according to user needs. LCAs conducted and being developed in different parts of the world generally differ from the others based on geographical, regulatory, economical, and perhaps, social variances. Germany, the Nordic countries and the European Community are considered as pioneers in environmentally-friendly manufacturing while the U.S. and Canada are working hard to develop their own regulations, standards and methodologies by learning from the experience of those Europeans [12].

Therefore, almost all software developed is different from others. Existing European LCA software includes CML SimaPro, German and Dutch VNCI. Due to the unavailability of LCA software, CML SimaPro (2.0 - Demo Version) which is developed by the Netherlands, is the only LCA software tested. SimaPro 2.0 is one of the first software systems utilizing the LCA methodology for product or process analysis. It is designed for users who want to use LCA data to analyze the contribution in terms of environmental impacts, of the different parts of the production in design projects. The program has an inventory and evaluation part, both filled with data. Data can be expanded and modified by users. It intends to support comparisons between different product alternatives by using the Ecopoints (NL) method. The higher the score, the greater the impact, (e.g. the greenhouse effect, the ozone layer depletion etc.). Moreover, because the program simplifies the complex nature of environmental impacts considerably, there are aspects which need to be improved.

Firstly, weighting factors, which indicate the relative contribution of an emission to the problem, need to be standardized; geographical differences especially should be carefully taken into account. Secondly, results obtained from the analysis are relative contributions rather than absolute offerings. Next, results generated may vary acutely or unpredictably as input values are changed, and this can lead to misinterpretations. Also, detailed data required by the program may not be as practical and accessible, as users would expect. In the user manual, it is stated by Mark Goedkoop, a PRé consultant specialized in SimaPro, "The reliability is therefore limited." Complete and detailed conclusions based on features and performance of this software cannot be obtained yet, in spite of the fact that the demonstration version of CML SimaPro has been tested.

2.9 Alternative Techniques

Approaches departing from the major theme of LCAs' development are being researched and established, as the difficulties of existing LCAs are considered to be not really solvable. A management approach has been proposed by Findlay, who defines "Managing" as a process to continuously measure, analyze and make improvements. It is explained that the three components of LCA implicitly demand a management system of environmental impacts. The management system approach consists of four components; they are requirement's definition, acquisition, utilization and disposal. Rather than use products or even product designs, which are too specific and cannot be generalized, the bases used in the approach are materials and processes. Boundaries are defined by the relevant process and organization. Advocates expect the complete management approach will be able to make optimum use of current organization, information, monitoring and decision-making systems to implement LCA concepts into an organization. Besides the management approach, the idea of using computer-assisted design methods such as the techniques of knowledge-based systems (KBS) commonly known as expert systems, has also been suggested by Benda *et al*. This idea owes its conception to the large amount of information associated with the development and use of LCAs. The use of a hierarchical classification (HC) which is a "task specific architecture" expert system approach is recommended. Currently, the use of the KBS in LCAs has been primarily limited to selecting an appropriate structure for representing knowledge about product life-cycles. Yet, the details of making the match between the need to organize knowledge to perform life cycle analysis and the ability of KBS approach to act as a template of representation will still be explored in the coming years.

CHAPTER 3

METHODOLOGY

The principal aim and objective of this thesis is to study the inventory analysis of major metals and glass used in a cathode ray tube (CRT) and also analyze and document the demanufacturing end-of-life stage of the CRT. So, to analyze and assess the environmental impacts of the metals and glass and also to formulate a disassembly procedure for the cathode ray tubes, the method of Lifecycle Assessment is used as a tool. This chapter introduces the methodology and procedure used for conducting the multi-lifecycle assessment or analysis of cathode ray tubes (CRT's).

3.1 Data Gathering

In any LCA study the availability and collection of data poses a major problem. It plays an important role in the whole process of conducting an LCA study. As, data is the basis of the entire LCA process, its sources and quality should be appropriately documented.

The research employed for this study consisted of several different categories ranging from raw material extraction to disposal and also an extensive literature survey related to LCA, industrial ecology, green design, environmentally conscious manufacturing and demanufacturing issues. Literature searches were conducted using various computer databases including library consortium, IEEE engineering database, and several standard environmental and engineering databases. Information related to LCA, green manufacturing, recycling and overviews of European initiatives / legislative programs was obtained through these searches. Extensive conceptual information was gathered by reading different environment engineering publications, IEEE journals, U.S. EPA guide to lifecycle assessment studies, and from various books such as Design for environment, Industrial Ecology, etc. Thesis reports in some past LCA studies were also referred and yielded some useful data. Internet was used extensively and proved to be the most effective tool in collecting data. Internet searches on the World Wide Web offered several useful sites pertaining to lifecycle assessment studies, electronics engineering, demanufacturing issues and industrial ecology.

Process data for various raw materials was gathered from books, journals, Internet and publications. The U.S. Department of Energy, U.S. Department of Ecological Survey, U.S. Pollution Prevention Clearing House were contacted for more specific data on energy requirements and consumption. Various associations such as the Aluminum Association, Copper Development Association, American Iron and Steel Institute, and the International Iron and Steel Institute were contacted to gather statistics and numerical data on quantity of raw material, energy, wastes, emissions, etc. Telephone interviews were conducted with representatives of some aluminum, steel, copper and oil industries. These conversations yielded significant information regarding the manufacturing process of these materials, their extraction and waste disposal. Finally, to gain a better understanding of the facilities being evaluated, site visits and interviews were conducted at steel recyclers, demanufacturing facilities, and Electronics Processing Association, Inc. (EPA Inc).

3.2 Lifecycle Assessment (LCA) Approach

This section of the chapter introduces the procedure used for conducting the lifecycle assessment of cathode ray tubes (CRT's). There is no doubt that product manufacturing has been worsening resource depletion. Considering that many material resources acquired from the earth are either limited or non renewable, material conservation must be decisively pursued. By doing that, a reduction of waste can also be achieved. Resources acquired from the earth, the so-called virgin materials, should be minimized. This research focuses on continuing the development of the inventory analysis concept which has been well defined and structured among all LCA components. The component of lifecycle inventory analysis for product materials, concentrates on quantifying the raw material requirement for the entire lifecycle of a product. At this stage, it is worthwhile to understand the concept, the background history, and the methodology used for any kind of lifecycle assessment study.

3.2.1 LCA Concept

The consumption of manufactured products, as well as the daily activities of our society, adversely affect supplies of natural resources and the quality of environment. These effects occur at all stages of the lifecycle of a product, starting with raw material acquisition through materials manufacture and product fabrication. They also occur during product consumption and a variety of waste management options such as land filling, incineration, and recycling. This has raised a high public concern and hence the government and industry have intensified the development and application of methods to identify and reduce the adverse environmental effects of these activities. To this end, lifecycle assessment adopts a holistic approach by analyzing the entire lifecycle of a product, process, package, material, or activity. It encompasses extraction and processing of raw materials; manufacturing, transportation, and distribution; use/reuse/maintenance; recycling; and final disposition. It does not analyze economic factors but can be used to create scenarios upon which a cost analysis can be performed.

Lifecycle assessment is a process to [22]:

- Evaluate the environmental burdens associated with a product, package, process, or activity by identifying and quantifying energy and material usage and environmental releases throughout their life cycle.
- Assess the impact of those energy and materials and releases on the environment, and
- Evaluate and implement opportunities to affect environmental improvements.

Figure 3.1 shows the various lifecycle stages.

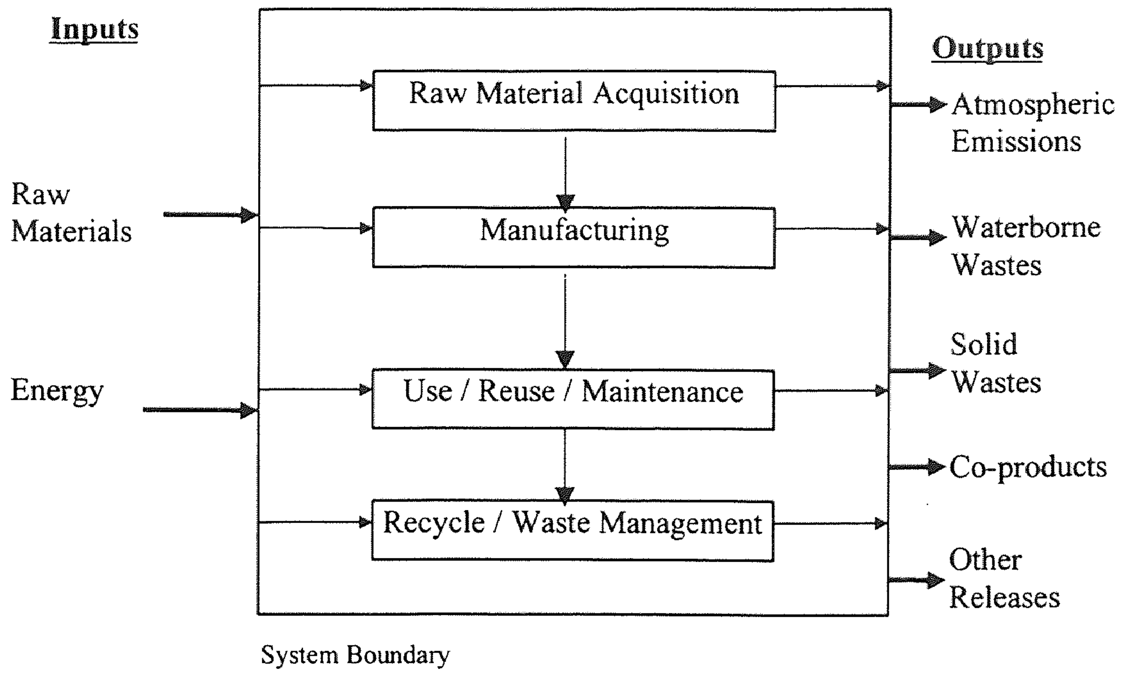


Figure 3.1 Lifecycle Stages
[Source: 21]

3.2.2 Background History of Lifecycle Assessment

Lifecycle assessment studies started in the 1960's. Concerns over the limitations of raw materials and energy resources sparked interest in finding ways to cumulatively account for energy use and to project future resource supplies and use. The Club of Rome's alarming report "*The limits to growth*" resulted in predictions of the effects of the worlds changing population on the demand for finite raw materials and energy resources and made the world aware that the natural resources are finite and the natural environment has limited capacity to absorb various pollutants. The foundation for the current method of lifecycle inventory analysis in the United States was established in 1969 when researchers initiated a study for the Coca-Cola Company. Various beverage containers were studied and compared to determine which produced the least negative effects on natural resources and the environment. Other companies in both the United States and Europe performed similar comparative lifecycle inventory analyses in the early 1970s and the process of quantifying the resources used and environmental releases of products became known as a Resource and Environmental Profile Analysis (REPA), as practiced in the United States and was called Ecobalance in Europe. However, in these studies, effects on human health and the environment were not considered. In the early 1970s, more research protocols were developed by the Midwest Research Institute (MRI). From 1975 through the early 1980s, as interest in these comprehensive studies waned because of the fading influence of the oil prices, environmental concern shifted to issues of hazardous waste management. But when solid waste became a worldwide issue in 1988, the lifecycle inventory analysis technique again emerged as a tool for analyzing environmental problems. Since then, a broad base of consultants and research institutes in North America and Europe have been further refining and expanding the methodology beyond the inventory to analyze the impacts of environmental resource requirements and emissions which brings lifecycle assessment methods to another point of evolution [21]. More recently, the Society of Environmental Toxicology and Chemistry (SETAC), and the U.S. Environmental Protection Agency (EPA) have served as focal points for technical development in the lifecycle assessment arena. Lifecycle assessment is often also known as Lifecycle Analysis (LCA), Lifecycle Review (LCR), Environmental Profile, REPA, Environmental Audits, Cradle-to-Grave Analysis, Ecobalance, Product Lifecycle Analysis (PLA), etc. For the purposes of this research, lifecycle assessment, lifecycle analysis and LCA will be used interchangeably.

3.2.3 LCA Methodology

The LCA methodology described in this section is a combination of guidelines prescribed by the U.S. EPA and SETAC. The three separate, but inter-related components of lifecycle assessment include: (1) the identification and quantification of energy and resource use and environmental releases to air, water, and land (inventory analysis); (2) the technical qualitative and quantitative characterization of the consequences on the environment (impact analysis); and (3) the evaluation and implementation of opportunities to reduce environmental burden (improvement analysis). Some lifecycle assessment practitioners have defined a fourth component, the scoping and goal definition or initiation step, which serves to tailor the analysis to its intended use. Figure 3.2 shows the technical frameowrk for conducting an entire lifecycle assessment study.

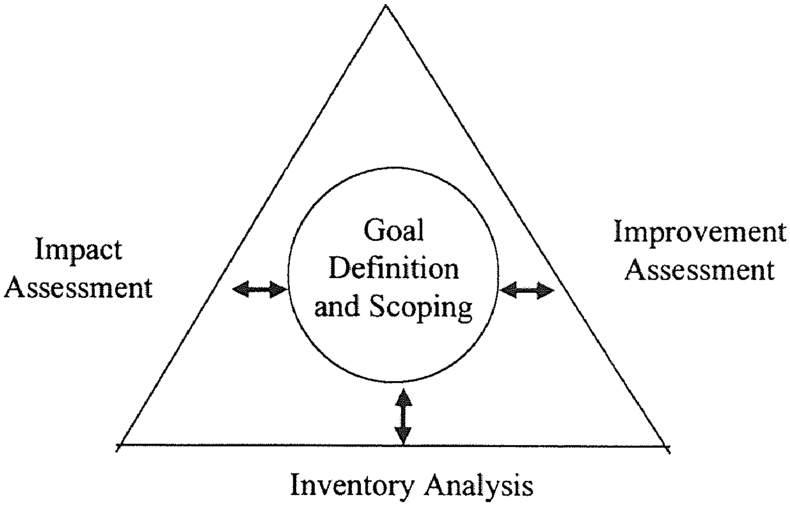


Figure 3.2 LCA Technical Framework
[Source: 21]

Lifecycle assessment is not necessarily a linear or stepwise process. Rather, information from any of the three components can compliment information from the other two. Environmental benefits can be realized from each component in the process. For example, the inventory analysis alone may be used to identify opportunities for reducing emissions, energy consumption, and material use. The impact analysis addresses ecological and human health consequences and resource depletion, as well as other effects, such as habitat alteration, that cannot be analyzed in the inventory. Data definition and collection to support impact analysis may occur as part of inventory preparation. Improvement analysis helps ensure that any potential reduction strategies are optimized and that improvement programs do not produce additional, unanticipated adverse impacts to human health and the environment [21].

The process flow chart for conducting a LCA study is described in figure 3.3 below. The four LCA steps are shown with their sub-components. These sub-components are not necessarily sequential but can be simultaneously carried out and hence shown likewise.

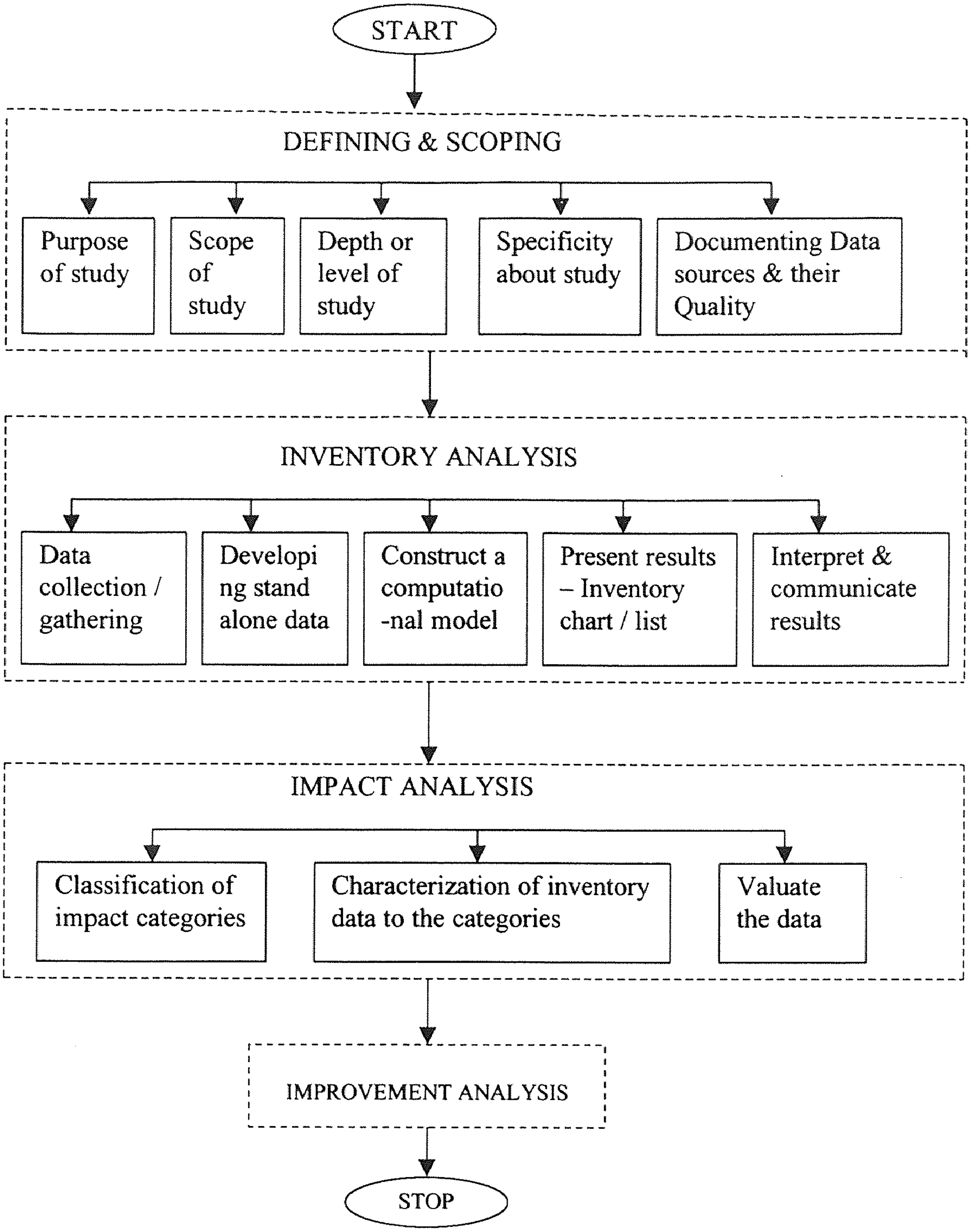


Figure 3.3 Process Flow Chart for Conducting LCA Study

Thus, LCA is a four-step process as described below:

1. Defining and Scoping: The sub-categories of this step are-

a) Purpose - Before conducting any LCA study, its important to define the purpose for conducting the study.

b) Scoping - This refers to defining the system boundaries for the intended study.

c) Depth - Here, the level at which the study should be conducted is defined. For example, first level study implies taking into account only those factors, which directly affect the material under study. The second level goes much deeper and considers the impact of production machines, their environmental impact aspects, etc.

d) Specificity - It should be specified whether the intended study is for any general or related to any specific process, activity, material, or product.

e) Data sources and quality – Each and every data or information generated during the study should be documented by identifying its source and also should be of good quality in terms of its authenticity. So, the level of confidence in the data should be high.

2. Inventory analysis: This is the only component of LCA that is well developed. Its methodology has been evolving over a 20 year period. The inventory analysis component is a technical, data based process of quantifying the energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire lifecycle of a product, package, process, material, or activity. Qualitative aspects are best captured in the impact analysis, although it could be useful during the inventory to identify these issues. In the broadest sense, inventory analysis begins with raw material extraction and continues through final product consumption and

disposal. Some inventories may have more restricted boundaries because of their intended use. The sub-steps in inventory analysis are as follows:

a) Data gathering - A system flow diagram in conjunction with the checklist and worksheets is usually helpful in gathering data for the lifecycle inventory analysis. Here, a system is viewed as a series of sub-systems. A sub-system is defined as an individual step or process that is part of the whole production system. Each sub-system requires inputs of materials and energy; requires transportation of products produced; and has outputs of products, co-products, atmospheric emissions, waterborne wastes, solid wastes, and possibly other releases. The material and energy sources used and the types of environmental releases are described for each sub-system. Also the actual activities that occur are described. Data for the amounts and kinds of material inputs and the types and quantities of energy inputs, the environmental releases to air, water and land are gathered and quantified. Coproducts from the process are also identified and quantified. For the purpose of this research and thesis a coproduct is defined as "A marketable by-product from a process. This includes materials that may be traditionally defined as wastes such as industrial scrap that is subsequently used as a raw material in a different manufacturing process" [21]. Finally the collected data should always be associated with a quality measure.

b) Develop stand-alone data - The individual sub-system module inputs and outputs for the specific product, process, or activity being analyzed should be standardized or normalized. Stand-alone data is a term used to describe this set of information developed. It is developed for each sub-system to fit the sub-systems into a single system. There are two goals to achieve, in this step. (1) Presenting data for watch sub-system consistently by reporting the same product output from each sub-system; (2) Developing the data in terms of the lifecycle of only the product being examined in the inventory. It is important to determine a standard unit of output for each sub-system. Lastly numerical relationship of the sub-systems within the entire system flow diagram is established.

c) Construction of a computational model - This step consists of incorporating the normalized data and material flows into a computational framework using a computer spreadsheet or other accounting techniques. The results obtained from these computations of the model give the total results for the energy and resource use and environmental releases from the overall system.

d) Presentation of the results - The data generated and the results obtained from the above two steps must be presented in a format that increases comprehension of the findings without oversimplifying them. Various types of tabular and graphical formats are used to present data in the form of inventory checklist and system boundary or inventory table.

e) Interpretation and communication of the results - The results of the lifecycle inventory should be interpreted depending on the purpose for which the analysis was performed. Data accuracy plays an important role in understanding or interpreting the results. For this, sensitivity analysis technique is applied. In this technique the inputs to a model are systematically varied in order to establish whether the outputs are distinguishable or not.

3. Impact Assessment: The impact analysis component is a technical, quantitative and/or qualitative process to characterize and assess the resource requirements and

environmental loadings (atmospheric and waterborne emissions and solid wastes) identified in the inventory stage. Methods for impact analysis are still in the early stage of development. The analysis should address both ecological and human heath impacts, resource depletion, and possibly social welfare. Other effects, such as habitat modification and heat and noise pollution that are not easily amenable to the quantification demanded in the inventory, are also a part of the impact analysis component.

The key concept in the impact analysis component is that of stressors. The stressor concept links the inventory and impact analysis by associated resource consumption and releases documented in the inventory with potential impacts. Thus, a stressor is a set of conditions that may lead to an impact. For example, a typical inventory will quantify the amount of SO_2 released per product unit, which may then produce acid rain which in turn might affect the acidification of a lake. The resultant acidification might change the species composition to eventually create a loss of biodiversity.

An important distinction exists between lifecycle analysis and other types of impact analysis. Lifecycle impact analysis does not necessarily attempt to quantify specific actual impacts associated with a product or process. Instead, it seeks to establish a linkage between the product or process lifecycle and potential impacts. The principal methodological issue is managing the increased complexity as the stressor-impact sequence is extended. Methods for analysis of some types of impacts exist, but research is needed for others. The following sub-steps are involved in an impact assessment study.

a) Classification - Here, the different classes of impact such as impact on human health, resource depletion, and ecological health, are decided.

b) Characterization - The inventory data available from the inventory analysis are assigned and characterized to the above classes of impacts. For example, a typical characterization would be of characterizing the impact of energy usage for producing a particular product on the resource depletion.

c) Valuation - In this step, the impacts are weighted and compared with some benchmark study already done. The major problem here is of comparison because everyone can set their own standards and weightage values.

4. Improvement analysis: The improvement analysis component of the lifecycle assessment is a systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw material use and waste emissions throughout the entire lifecycle of a product, process, or activity. This analysis may include both qualitative and quantitative measures of improvement. Tools such as continuous improvement, design for environment, and total quality management are being used in these regards. Finally this component has not been widely discussed in a public forum. These sums up the generic methodology used to conduct lifecycle assessment of any product, process, or activity.

3.3 Multi-Lifecycle Assessment - A New Approach

Lifecycle assessment methodology described earlier is the traditional framework set up jointly by the U.S Environmental Protection Agency (EPA) and Society for Environmental Toxicology and Chemistry (SETAC). It considers all the lifecycle stages of a product, process, or activity from raw material extraction to final disposal. Multi-Lifecycle assessment (MLCA) also addresses these lifecycle stages beginning from raw material extraction to final disposal, but differs from traditional LCA in the last stage and in the overall perspective of thinking about the LCA methodology.

The term multi-lifecycle is relatively new. This term emphasizes the fact that technology developed here would enhance the use of discarded scrapped products, or other waste-streams so that materials and components can be used over more than a single product lifecycle. In this respect MLCA does not differ quantitatively in terms of inventory analysis as compared to traditional LCA, but tries to develop a systems perspective towards this area. It looks backwards in time to designing products such that the materials used in them have multiple lives and thus uses after their first useful life. This requires a clear vision and understanding of the product from its raw material extraction till its usage. And hence efficient demanufacturing of the product is one of the prime goals of multi-lifecycle engineering. Design for disassembly helps in attaining this goal and efforts are being made towards developing a methodology for it.

At every stage of Multi-Lifecycle assessment methodology one has to consider the various inputs and outputs that enter and exit that particular stage. A stage here is defined as an entity in itself which is transformed to some higher or lower state by performing a process or activity on that stage. Thus, developing and defining a generic process model is essential for implementing the MLCA methodology, as every lifecycle assessment study can be implemented in different way depending upon the analyst. So, the generic process modeling structure for a system that is developed and implemented for MLCA study purpose is shown in figure 3.4.

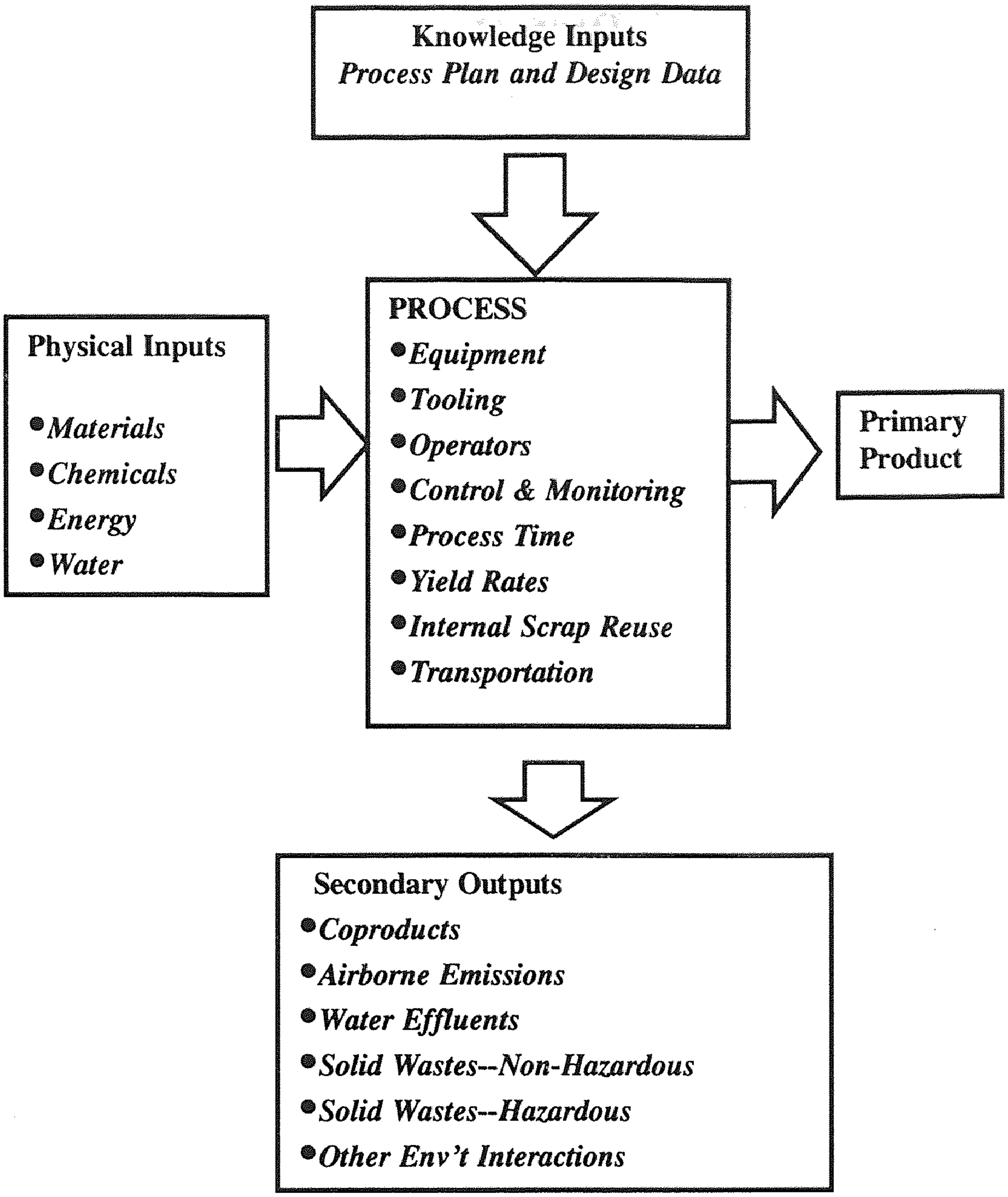


Figure 3.4 Generic Process Modeling Structure for a System

The center of the figure indicates any stage of LCA, such as raw material extraction, manufacturing, use/re-use/maintenance, and demanufacturing, to be analyzed. There are various necessities required for the process to take place. Some of these such as equipment, tooling, operators, etc. are shown in the process model. The left side indicates the physical inputs required for the process to take place. These inputs are in the form of raw materials, chemicals, energy, and process water required for conducting the process or activity.

The traditional approach is to use these physical inputs which give outputs in terms of required primary product and secondary outputs. The secondary outputs are the undesirable portion of the process but are inevitable and so play an important role in assessing the environmental burdens of a product throughout its lifecycle. So, the traditional LCA approach only takes into account these burdens and impacts, but do not define a definite approach or methodology towards that end. But, the generic process model developed for Multi-Lifecycle assessment methodology addresses this need by having a separate input called as the knowledge inputs, which logically flow into the process model along with the physical inputs. The knowledge inputs are in the form of a process plan and design data that influences the process under consideration.

The basic logic behind having these inputs is to design and plan the process in such a way that the secondary outputs, mentioned earlier, can be of some commercial use, which in terms also reduces their environmental burden and impact over the products entire lifecycle. The knowledge inputs integrates the various stages of the lifecycle of a product and acts as a linkage between each process of the LCA stage and back to the products design and operational considerations. Thus, knowledge inputs basically formalizes this linkage. And hence this type of design and process planning activity links directly to the design for environment goals of a company and helps achieve a much cleaner and environment friendly process.

The last stage in the traditional LCA is of recycle/waste management. It has only three options namely recycle, compost, or discard the waste generated after the full usage of the product. The main option to consider and where MLCA differs from LCA is the recycling of the product. LCA addresses two types of recycling processes, open loop recycling and closed-loop recycling. Closed-loop recycling occurs when a product is recycled into a product that can be recycled over and over again. Whereas in open-loop recycling system, a product made from virgin material is recycled into another product that is not recycled, but disposed off, possibly after a long-term diversion. So, LCA looks into this as two separate distinct recycling options.

This is where MLCA plays its role, in addressing these two recycling options simultaneously, rather than in isolation, and not only at the end of products life but also throughout its life from raw material extraction to final disposal. MLCA calls this last stage of product life cycle as Demanufacturing. It encompasses following sub-stages or options for the disposal of the product as shown in figure 3.5.

Traditional LCA talks about recycling in which some material is ultimately disposed to land as in closed-loop / open-loop recycling. Thus, LCA is a cradle-to-grave analysis, whereas MLCA tries not to landfill any material as far as possible and so is a cradle-to-cradle analysis tool. MLCA finds new options for the waste disposed at every stage so that it can be re-engineered into useful products and not just once but again and again.

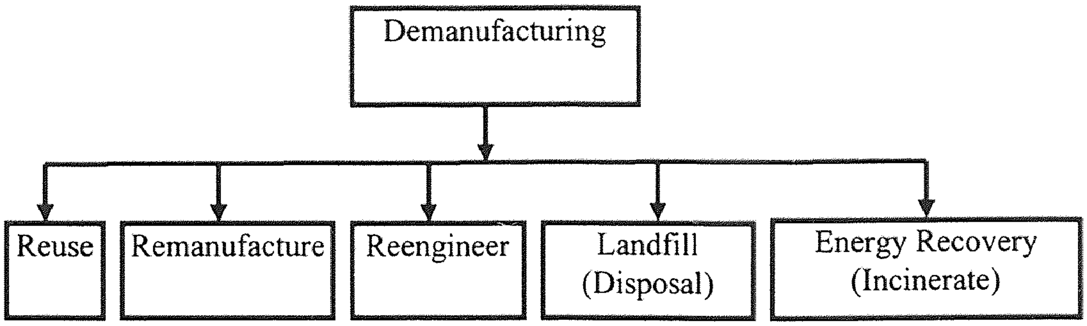


Figure 3.5 Demanufacturing Sub-stages

Therefore, the whole system perspective of having multiple lives for a product or material is termed as Multi-Lifecycle Engineering. Figure 3.6 shows the total lifecycle engineering framework in terms of the considerations for analysis and modeling.

At every stage (box) in this framework, the inputs in terms of energy, materials and water are balanced with the outputs in terms of primary product, solid wastes, emissions and water effluents. The optimizing criteria to achieve this balance depends upon the technological, economical and ecological trends and its scope is wide ranging from corporate, state / regional, national to global level. This generic process model is for the system as such and thus can be incorporated at any level of analysis. Further, in the inventory analysis chapter a generic process model for primary and secondary production of raw materials is developed, which is specific to them.

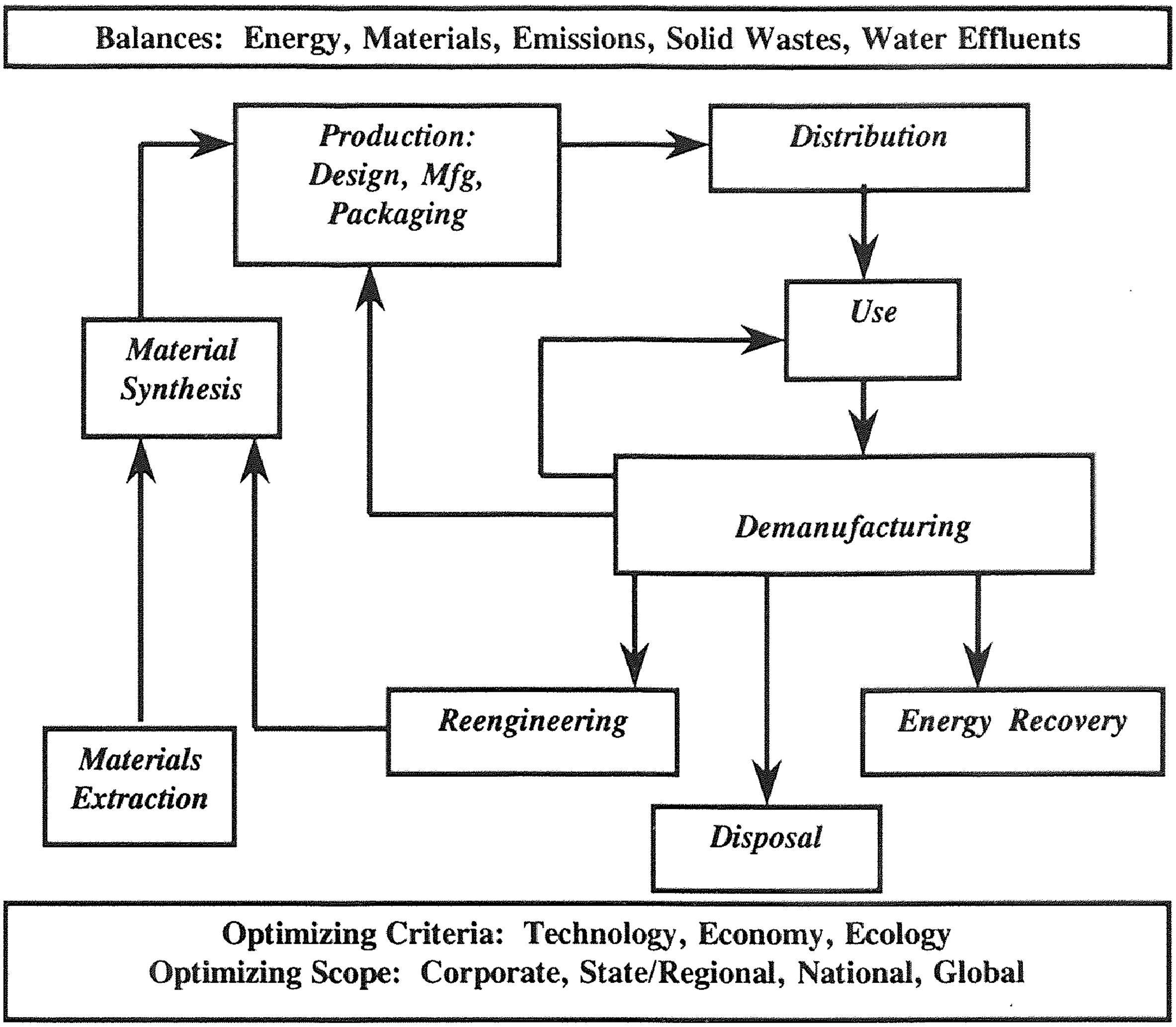


Figure 3.6 Total Lifecycle Considerations for Analysis and Modeling

Figure 3.7 shows the Multi-Lifecycle considerations on LCA. This figure and the following equations emphasize the effect of Multi-Lifecycle concept on the requirement of virgin material for a product.

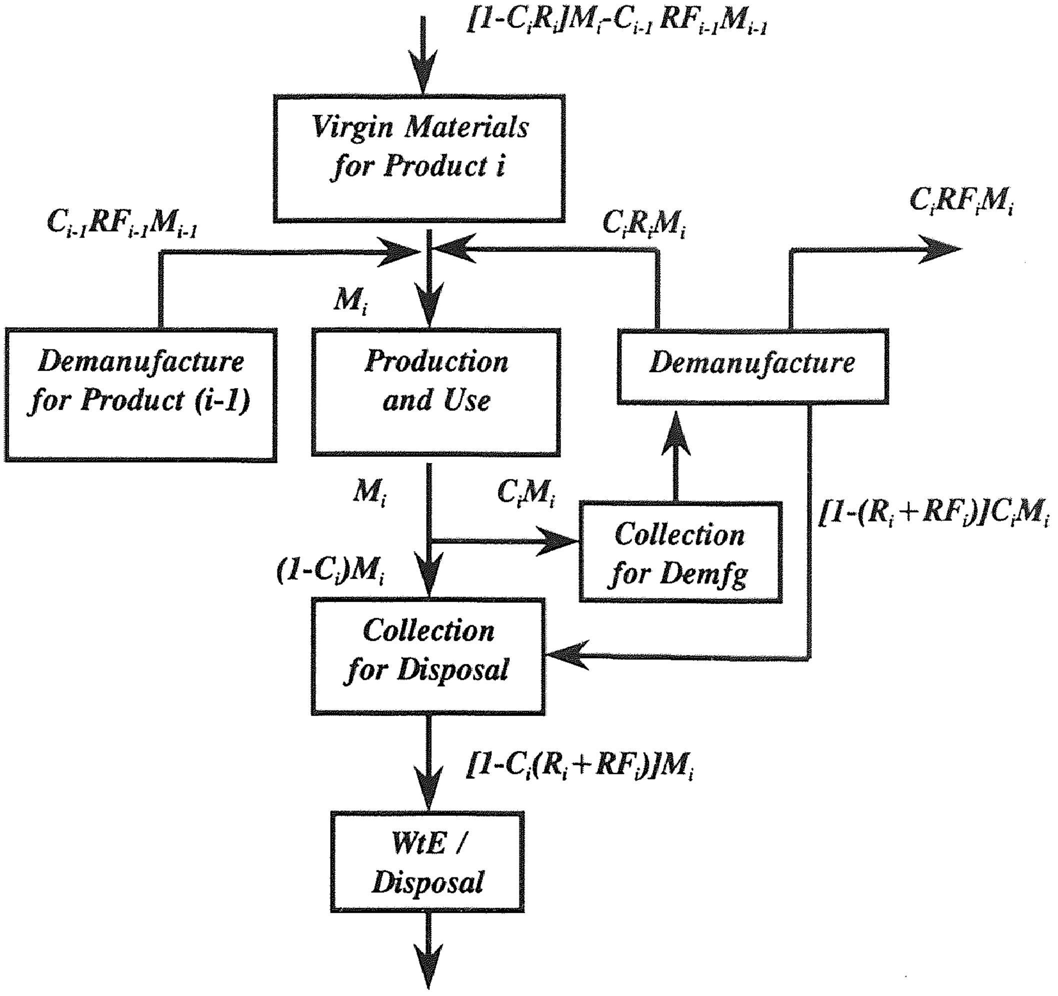


Figure 3.7 Multi-lifecycle Considerations on LCA

Thus, the multi-lifecycle considerations on LCA shown in figure 3.7 can be analyzed as below. These considerations for a product are form raw material extraction stage to the final disposal stage. The diagram essentially demonstrates the raw material impact on the lifecycle of a manufactured product.

Explanation of the terms used in figure 3.7 is as follows,

i = product

M_i = mass of material required

C_i = fraction of M_i that can be demanufactured

R_i = fraction of demanufacturable material going back into product i (closed-loop recycling)

RF_i = fraction of demanufacturable material going into other product (open-loop recycling)

Analysis:

Virgin material required for production of product i = M_i.

Material available for disposal after production and use = M_i.

Material collected for demanufacturing = C_iM_i.

Therefore, material collected for disposal = $(1 - C_i) * M_i$.

Material going back into production of i after demanufacturing = $C_iR_iM_i$.

Material that goes into production of other product after demanufacturing = $C_iRF_iM_i$.

Therefore, waste material from demanufacturing = $[1 - (R_i + RF_i)]C_iM_i$.

Therefore, total waste / disposal =

$$(1 - C_i) * M_i + [1 - (R_i + Rf_i)]C_iM_i = [1 - C_i(R_i + RF_i)]M_i.$$

Material available for production of i from demanufacture for product (i - 1) =

$$C_{i-1}RF_{i-1}M_{i-1}.$$

Therefore, virgin material requirement for product i =

$$M_i - C_iR_iM_i - C_{i-1}RF_{i-1}M_{i-1} = [1 - C_iR_i]M_i - C_{i-1}RF_{i-1}M_{i-1}.$$

These equations show the impact of multi-lifecycle considerations on traditional LCA concept. The major consideration here is the allocation of benefits to the product, when it can be demanufactured effectively and its sub-assemblies, components, and materials can be reused again and again. This lowers the overall impact of the product over its total lifecycle. This also emphasizes the fact that if after demanufacturing the product, its sub-assemblies, components, and materials can be used for other products or can lower the virgin material requirement of other products (by reengineering the materials obtained from the demanufactured product) then it is a more green product. And hence it should be allocated with benefits, for lowering its own impacts.

Thus, this MLCA methodology has been applied throughout this research and also in the thesis.

CHAPTER 4

OVERVIEW OF CATHODE RAY TUBES

The display system or screen is one of the most critical components of a television and is the largest and heaviest component. The predominant display technology is the cathode ray tube (CRT), which provides a rich high-resolution display well suited to a wide range of user requirements. Other techniques like vacuum fluorescent, plasma panels, and electro-luminescent panels find significant use in industrial and instrumentation applications, while CRT is the display of choice for both televisions and computer displays.

4.1 CRT Markets

The CRT's manufactured in the U.S. are mainly for the color-television industry and the monochrome, industrial, and military industries. Television dominates the installed display base, both in terms of size (the 19 to 27 inch viewing diagonals TV's dominate the marketplace) and ubiquity. Computer displays are also becoming pervasive with sales exceeding 8.8 million (one third as large as TV's) in 1992. Other markets of CRT for the industrial and instrumentation use, number in terms of millions of displays per year, but due to their smaller size do not constitute an equivalent environmental impact.

The following table shows the trend of increasing color TV CRT manufacturing in the U.S., which grew by 43% from 1986 to 1992 and decreasing monochrome manufacturing.

Table 4.1 Sales Reported by EIA Manufacturing Companies.
[Source: 22]

Year	1986	1988	1990	1992
Color CRT's	11,684,000	13,747,000	14,600,000	16,741,000
Monochrome CRT's	3,959,000	2,580,000	1,411,000	633,000

TV's, computers, oscilloscopes, and other testing and measuring devices will continue to be a strong market, although future development of multimedia entertainment systems and high-definition television is also expected to drive the market for CRT's. The CRT continues to be the predominant display technology due to its cost per pixel and high-quality display. Flat-panel technologies have begun to mature and are expected to displace CRT's in some market segments.

4.2 CRT Manufacturing

The US CRT manufacturing industry primarily produces color picture tubes, single phosphor tubes, and rebuilt tubes [23]. The CRT manufacturing industry is made up of three different categories of manufacturers, in the US. These three categories are the CRT glass manufacturers, CRT tube manufacturers, and the CRT assemblers [23]. Two major kinds of CRT's are manufactured namely monochrome CRT's and color CRT's. There are many different designs in these depending upon whether it is a monochrome or color CRT.

4.2.1 CRT Components and Description

The four major parts comprising a CRT are: the glass panel (or faceplate), a shadow mask (aperture, contained within the glass panel), a glass funnel, and an electron gun. Fig. 4.1 describes a typical monochrome CRT.

There are some additional components in a color CRT including an internal magnetic shield. The electron gun is housed at the back end (neck) of the CRT by the glass funnel. A glass frit solder holds the glass panel and glass funnel together. The other components in an assembled television include a plastic cabinet, electromagnetic shields, circuit boards, connectors, cabling and other discrete components. The research presented here concentrates on the CRT itself, rather than the other parts of the overall display. Also, in general, CRT's manufactured for households are the same as of those manufactured for business and the composition of television and computer CRT's are not substantially different [24] .

A recent US EPA study provided an inventory of primary materials of a typical color CRT, which is shown in table 4.2. As seen from the table, in color CRT's the panel or the faceplate doesnot contain much lead. Infact in some color CRT's there may be even zero percent lead. But then other materials such as strontium, and zirconium are present, which increases the cost of the color CRT's and also makes the production of the panel much difficult.

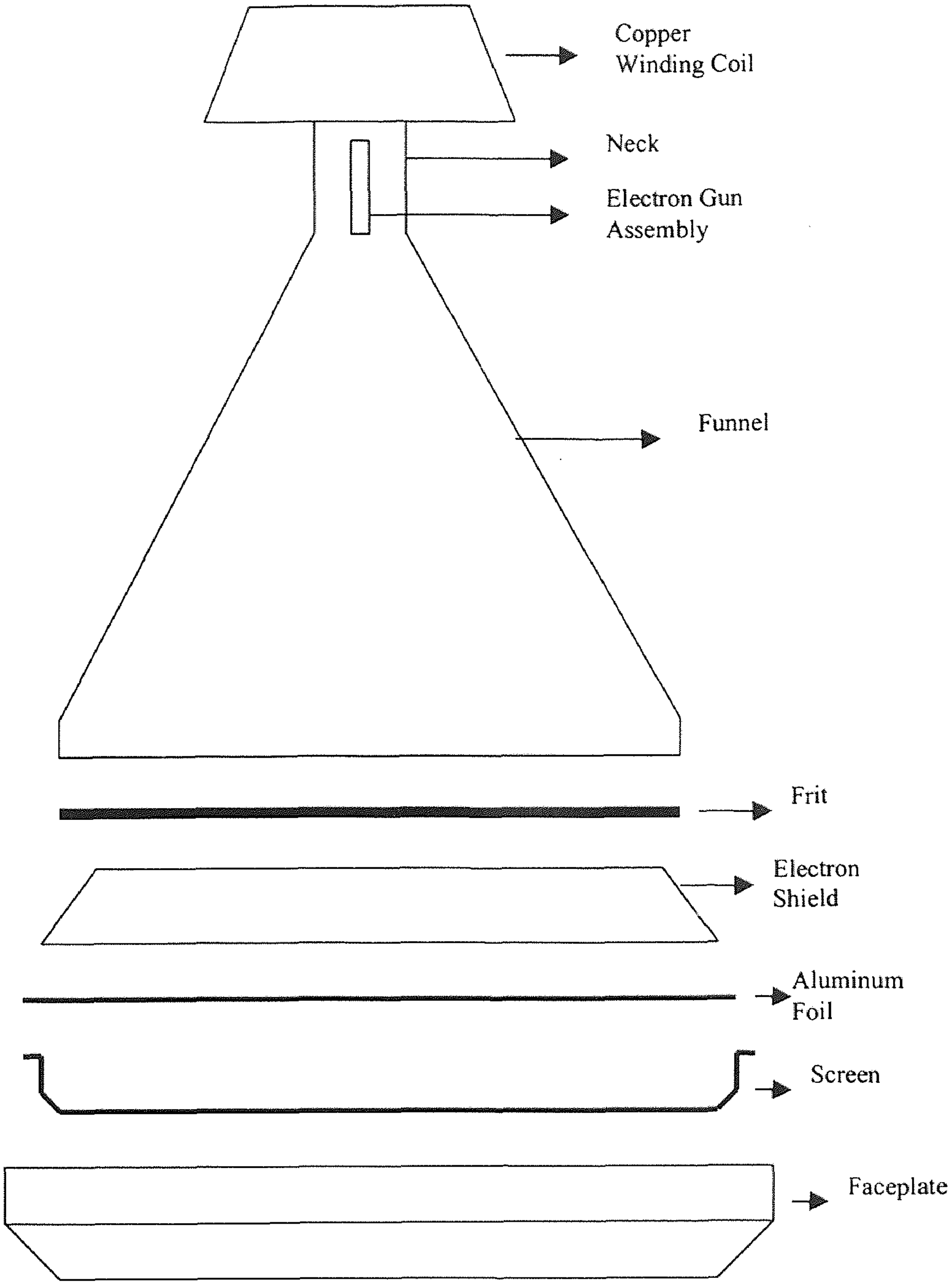


Figure 4.1 A Typical Monochrome CRT

Table 4.2 Primary Materials in a Typical 20 inch Color CRT
[Source: 23]

No.	**Component**	**Material**
1	Panel	2% lead glass
2	Funnel	28% lead glass
3	Grille	Aquadag (These are the suspensions of electrically conductive carbon materials with silicate binders in a water suspension).
4	Phosphors	ZnS, YOS
5	Aluminizing	Aluminum
6	Conductive coating	Aquadag, Iron Oxide powder.
7	Shadow mask	Steel
8	Shadow mask frame	Steel
9	Spring clips	Spring Steel
10	Washer	Steel
11	Magnetic shield	Steel
12	Electron gun	300/400 series steels, borosilicate glass, nickel, cathode coat.
13	Base	Plastic
14	Implosion band	Steel
15	External coating	Aquadag

4.2.2 CRT Production

The CRT is manufactured by fabricating four subassemblies as follows: 1) the phosphor coated faceplate, 2) the shadow mask assembly, 3) the conductivity coated funnel, and 4) electron gun. A quick overview of the CRT assembly process is shown in figure 4.2 below.

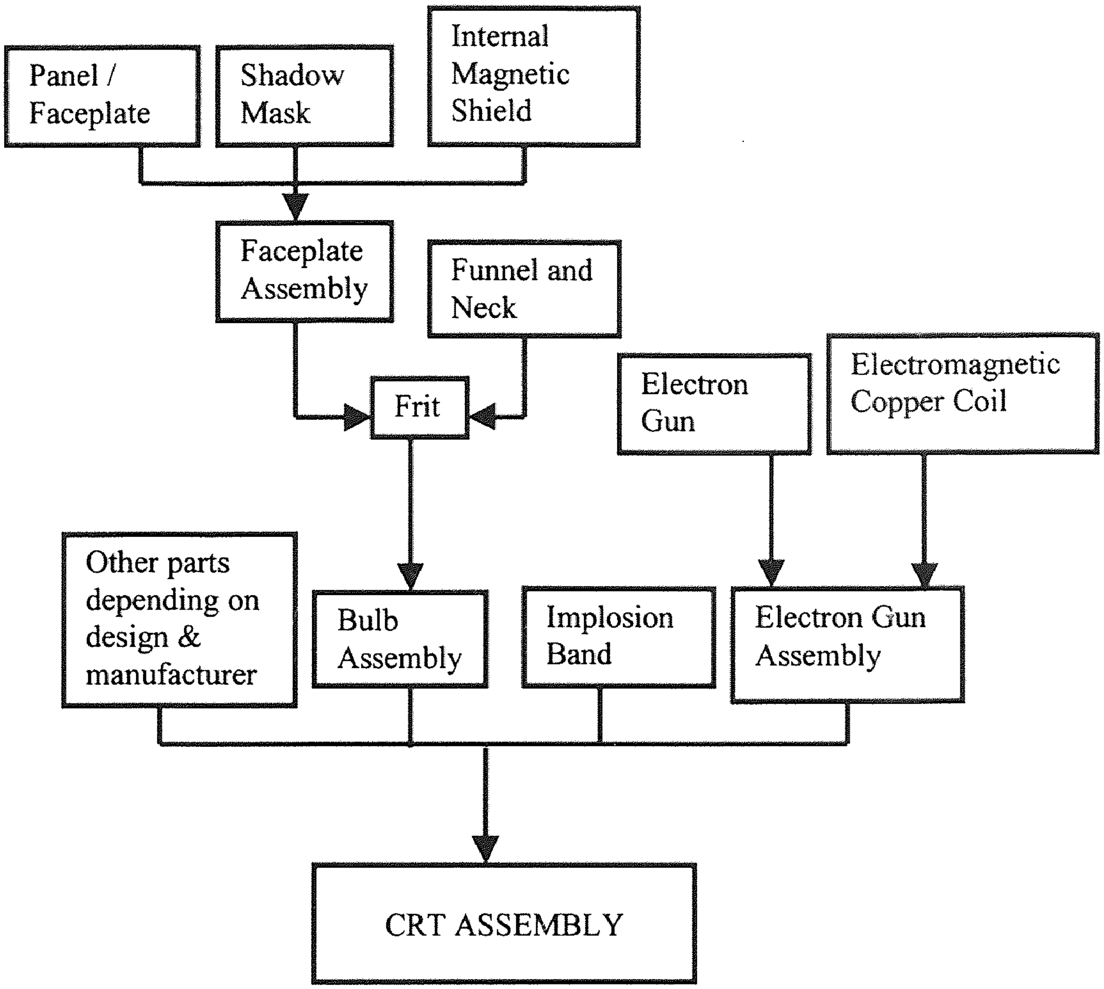


Figure 4.2 CRT Assembly Process

The typical manufacturing process for each of these sub-assemblies is described as follows [25]:

Faceplate: Spin coaters are used to apply the luminescent phosphor and contrast enhancing grille materials to the inside surface of the faceplate in aqueous solutions. Photolithography is employed to pattern these coatings using polyvinyl alcohol (PVA) photoresists and near-ultra-violet exposure lamps. The exposure light is projected through the shadow mask assembly to place the phosphor elements in precise registration with the apertures in the shadow mask. Red, green and blue phosphor coatings are applied in desired patterns. This is done after applying a contrast enhancing layer of grille dag. Finally, over a lacquer leveling film, a reflective layer is applied. The total screen layer measures less than two thousands of an inch thick.

After the dichromate-sensitized PVA photoresist in a water solvent is applied to the faceplate, the shadow mask is attached temporarily to the faceplate. A light passed through the apertures in the shadow mask causes exposure of the photoresist material resulting in a pattern of dots (or stripes) where red, green, and blue phosphors are to be placed in subsequent steps. This pattern is developed by rinsing with water, and the unexposed resist is washed away. A coating of contrast enhancing material (grille dag) is then applied and dried. Due to its volatizing ability, PVA is a desirable material during the thermal processing of the CRT. About 1% ash remains, and does not significantly change the light production efficiency of the phosphors.

A lift-off process digests the resist, which remains between the glass and the grille material. The digested resist lifts off the glass, which carries away the grille material on top of it, and opens the windows in the black grille material. In subsequent coating and photolithographic steps, the red, the green and blue phosphors are placed in these windows. The result is a patterned luminescent screen with the emissive elements separated by the non-reflecting grille materials. The phosphor materials are powders which are applied one at a time in dichromate sensitized PVA slurries. The light exposure polymerizes the material in the windows, so that after development, the next material can be applied immediately. After the grille and three phosphor patterns have been applied, the reflective aluminum layer is processed. The screen profile is quite rough because the phosphors are granular and the leveling coat is applied before evaporating the aluminum over the screen. Lacquer is applied as an emulsion film or spread directly on the screen, and then dried. Then the assembly is placed on a vacuum system and aluminum is evaporated over the lacquer at a little more than 1000A. Now, the panel is ready to be joined to the funnel.

Funnel: The funnel is the back half of the vacuum shell and electrically connects the electron gun and the faceplate to the power supply via the anode button. It has an aquadag coating on the inner surface. Funnel dag is applied by sponge, by flow coating or by spraying. The solvent water is then evaporated in an oven. A toothpaste consistency free (solder glass frit) coats the panel mating surface of the dry funnel. This frit is a low melting temperature glass made with lead oxide, zinc oxide, and boron oxide.

Shadow mask assembly: This is a thin foil member made of aluminum-killed steel which is etched with appropriate pattern of round apertures, slits or slots. Shadow masks are produced in the U.S. for the television industry. They use low resolution patterns created by coating the mask foil with a casein type resist, patterning by photographic copy with ultra-violet lamps, developing the pattern and etching out the apertures with ferric chloride etching solution. The ferric chloride etchant is reduced by the dissolving iron, producing ferrous chloride from both the etchant and the dissolving iron. The etchant is regenerated, producing by-product iron chemicals and ferric chloride.

The flat mask is curved to approximately the shape of the faceplate in a large hydraulic press. The mask is supported on a metal frame inside the CRT. Springs are welded to the formed frame and the shadow mask is welded on while the parts are held in an alignment fixture. For increasing the brightness capability of the finished CRT, the parts are oven blackened. The mask, which is introduced into the CRT process, has the exposure master for placement of the screen mosaic and is subsequently assembled into the CRT.

Bulb joining: A faceplate assembly is formed by joining the panel, shadow mask assembly, and internal magnetic shield together with clips. This assembly is placed on the fritted funnel in a fixture, which will carry the two halves in a precise alignment through a high temperature oven, which cures the frit. The resulting assembly is a vacuum tight bulb, ready to become the CRT after receiving the electron gun and evacuation.

Electron gun: A number of electrostatic field shaping electrodes made of 300 and 400 series steels mounted on insulating glass pillars form the electron gun. Three cathodes located, within the lower end of the gun, consist of hollow nickel tubes with one end closed and coated with an electron emitting material, typically a mixture of barium, strontium and calcium. At the center of the cathode tube, a tungsten wire heater is placed. The steels in this industry contain iron, nickel, and chromium. A combination of barium, strontium and calcium carbonates forms the emissive material. The tungsten wire heater is coated with a layer of aluminum oxide insulation. The glass support pillars are made from borosilicate glass.

Before assembly, the high purity electron gun metals are typically hydrogen fired and precisely fixtured together before attachment of glass pillars. The glass pillars are heated to their softening temperature and pressed over tabs on the metal electrodes. The pillars encapsulate the electrodes as they cool, thus making a monolithic structure. This structure is mounted to a glass stem, which will be joined to the neck portion of the bulb assembly by melting. For carrying the electrical connections from the external circuitry to the electrodes, the glass stem is provided with electrical feed-through pins.

The cathodes are inserted into support electrode after the monolithic grid structure is formed and the heater is inserted. Then the assembly is welded to the support pins in the stem. Between the upper electrodes and the remaining pins on the stem, additional ribbon conductors are welded. Finally, the upper cup of the gun, steel centering springs and a vacuum getter ring on a long wand are welded on. Various parts are added at this stage. Anti-arcing wires or magnet pole pieces or magnetic shunts may be welded in place, depending upon design. The finished electron gun assembly is ready for sealing to the bulb.

Exhaust/Finishing: The stem and neck tubing are fused together for joining the frit sealed bulb assembly and the electron gun. This is done in a gun seal machine that melts the two glasses together. The two pieces are fixtured into precise alignment during this fusion operation. The neck is slightly longer than necessary, and the extra glass is "cut off" by the sealing fires and the excess neck cullet falls into a reclaim container. The cullet material remains pure neck glass, and is thus returned directly to the glass companies to be remelted and reformed into new necks.

The entire CRT, after joining, is attached to a vacuum exhaust machine, which carries the assembly through a high temperature oven while exhausting the air from inside the CRT. The combination of high temperature while pumping the air out of the CRT produces a high vacuum inside. After cooling, the vacuum getter is vaporized and the evaporated metal (barium, zinc) coats the inner surface of the CRT. The residual gases inside the envelope are absorbed by this film, thus reducing the gas pressure inside the CRT to its final operating pressure.

The electron emissive cathode material, which was initially sprayed on the nickel cathode cap in a carbonate form, is first converted to an oxide form by electrically heating the cathode to high temperature. While at high temperature, an electrical current is emitted from the cathode, thus reducing the surface metal oxides to a monolayer of metal. The resulting surface emits large quantities of electrons, which can be controlled by voltages applied to the electrodes of the gun.

Testing is then done on the CRT to insure that all of the coating, assembly and finishing processes were successful. Automatic electrical tests and visual appearance checks are employed. After the CRT confirms acceptability, the CRT implosion safety attachments are applied, the product is tested again, and packed for shipment to the display assembly factory. This completes the entire fabrication process for a color CRT. This process may differ from manufacturer to manufacturer, depending upon the types of materials used in the CRT.

4.3 CRT Technology and Functioning

The following section describes the functioning of a color CRT. Electrons are accelerated using high voltages towards the faceplate. The phosphor in the faceplate converts the kinetic energy of the electron into light. In a color CRT, the phosphors are patterned in dots or stripes of red, green and blue phosphors. The glass panel is screened from the inside using a carbon stripe process and the phosphor stripe process. Three electron guns corresponding to red green and blue colors emit electrons, which are deflected across the screen by the electromagnetic deflection yoke. The shadow mask filters the electrons so that electrons from each gun excite only the associated color phosphor, creating an image on the luminescent phosphor screen.

4.4 CRT Dilemma: Environmental Issues and Concerns

Though CRT is the prominent display technology in use today, it is faced by considerable amount of recycling and environmental problems. Due to rapid growth of technology and decreasing costs of televisions and computers, the new improved products reach the market very quickly, and so the installed base of old products become obsolete long before they reach the end of their useful lives. This results in many customers replacing the equipment frequently. As a result of this, over two decades of consumer electronic market growth, the volume of electronic products available for disposal is very large and continues to grow year after year.

The discarded televisions from households are treated as other solid wastes and enter the municipal solid waste (MSW) stream. But in future, the changing environmental regulations and scenario for the disposal of the televisions and most of the electronic products in the MSW facilities will be of concern because of the presence of toxic substances in these products, and also due to their bulkiness. When these products are landfilled, heavy metals may leach from these products into the ground water, in addition to occupying landfill space. If incinerated, trace amounts of heavy metals may be released into the air, and subsequent landfill disposal of ash may result in the leaching of metals to ground water. Following sections describe the toxic substances, physical characteristics, and other factors including their possible environmental impacts of concern specific to the CRT industry. Some regulatory, risk and logistical factors are also considered.

4.4.1 Toxic Substances of Concern in CRT

The CRT glass contains substantial amount of lead, especially the funnel and the neck portion of the CRT contain almost 30% lead in them. Lead, which is used to shield harmful radiation, comprises more than 10% of a CRT's mass[]. Other metals like cadmium, copper, zinc, strontium, barium are also present, but in significantly lesser amounts.

4.4.2 Physical Characteristics of Concern

The CRT is comprised of a combination of glass, metals, and plastics. The glass itself is of six different compositions and engineering requirements, as shown in Table 4.3

Table 4.3 Glasses in Television and Display CRT's.
[Source: 25]

Component	Composition	Forming	Critical Requirements
Panel	Zero to 2.5% lead oxide alkali/alkaline earth aluminosilicate	Pressing	Optical Quality, x-ray resistance, color and tint control.
Funnel	22% lead oxide alkali silicate	Pressing or spinning	High x-ray resistance, viscosity control.
Neck	30% lead oxide alkali/alkaline earth silicate	Tube drawing.	Thermal expansion match to metal wire feedthroughs; x-ray absorption.
Stem	29% lead oxide alkali aluminosilicate	Tube drawing.	Expansion match to metal wire feedthroughs; x-ray absorption.

Table 4.3 (Cont.) Glasses in Television and Display CRT's.
[Source: 25]

Gunmount	Potassium aluminosilicate sintering	Tube drawing.	Crystallization
Frit	70% lead oxide zinc borate	Powder sintering and crystallization	Low temperature

These materials are used in the CRT for different characteristics and attributes such as structural integrity, durability, are some x-ray absorbing capabilities. But these same characteristics and attributes present municipal solid waste disposal problems. For example, the landfilling of these materials together requires substantial land space and also their incineration can result in toxic emissions of ash. Table 4.4 shows the breakdown of different materials in computers and televisions.

Table 4.4 Computers and Televisions: Durable Materials Content
[Source: 4]

Material	**Computer (% weight)**	**Television (% weight)**
Plastic	23	15
Metal	52	20
Glass & Ceramic	25	65

Primary and mining wastes produced during the mining and smelting of raw materials required for the CRT and the television include iron, aluminum, strontium carbonate, and emissions of silicon dioxide, sulphur dioxide, lead oxide, carbon dioxide, and carbon monoxide. So, these issues should also be addressed within the multi-lifecycle framework of the CRT.

Remaining factors such as material identification for recovery, waste/sludge disposal during washing operations, display housing which is plastic, power consumption during manufacturing and use, also play an important role and should be appropriately dealt with.

4.4.3 Impact of Toxic Substances on the Environment

Lead: Lead is a known toxic metal. Exposure to lead in any form may lead to effects such as reduced growth in children, lessened reaction time, weakness in fingers, wrists or ankles in adults. Lead also affects human memory and the kidneys. There is no threshold level established for adverse effects for lead and EPA has not stated a reference dose due to the fact that there may not be an intake level that is completely safe for children. Thus, it is one of the substances that are of greatest environmental concern.

Cadmium: The largest sources of cadmium release to the environment are the burying of fossil fuels and the incineration of municipal solid waste. Among others, lead and copper smelters are also sources of airborne emissions of cadmium. Food materials tend to take up and retain cadmium. So, food is the primary source of exposure to cadmium for many people. Cadmium causes health problems such as irritation of stomach and toxicity to lungs and kidneys. Cadmium retains in a human body for a longer period of time, so even lower amount of doses may be harmful as they can accumulate and lead to lung cancer, or damage kidneys, liver, as well as the immune system and blood. Thus it is important to note that cadmium too is a substance of environmental concern.

Zinc: Although zinc is a toxic substance of concern, it is an essential nutrient needed by our body in small amounts. Too little zinc in the diet can lead to poor health and decreased immune function, but too much can cause gastrointestinal problems, anemia and can also damage the pancreas. Zinc enters the air, water and soil during mining activities, combustion of coal and solid waste, air and wastewater discharges from metal manufacturing and disposal of zinc wastes and zinc-bearing ash from coal and waste combustion.

Copper: Copper enters the environment through mining, metalworking, copper protection, and manufacturing of copper-bearing products. Human beings can be exposed to copper through drinking water, inhaling dust, or contacting soil or water contaminated with copper. Apart from being an essential element of living organism's, high level exposure to copper can cause irritation of eyes and mouth, headaches, nausea and dizziness. Very high level of chronic exposures may even cause death.

Other concerns: There are various other factors of concern in a CRT during its manufacture, use and disposal. CRT manufacturing concerns are mainly related to nitric acid use, and removal of air from inside of the tube. This may lead to health and safety risks for the workers. The greatest environmental issue is the large weight and significant volume of the display and therefore the corresponding need for significant space in landfills. The weight of the sample 14" CRT disassembled at the MERC Demanufacturing Laboratory was almost 13 pounds. Thus, the weight of 20" CRT's may well exceed 30 pounds. The Electronic Industries Association (EIA) estimated that the rate of manufacture of color CRT's in north America is 16million CRT's per year and adds approximately 500 million pounds of glass annually to the CRT products in use. An additional 5 million televisions are imported bringing an additional 12 million CRT's a year into the U.S. [25].

The CRT, in addition to glass, contains deflection yoke, plastic cabinet, electromagnetic shields, circuit boards, copper coil connectors, and discrete components. So, for practicing recycling cost effectively, the CRT has to be designed for easy disassembly. But this requirement is in contrast to the normal design goal of structural rigidity, safety interlocks, and other objectives.

4.4.4 Regulatory, Risk and Logistical Factors

The main act that strictly regulates the nation's hazardous wastes is the Resource Conservation and Recovery Act (RCRA). It mandates that solid wastes exhibiting certain characteristics such as corrosivity, toxicity, reactivity, and ignitability, be managed as hazardous wastes. But household consumers who, use televisions and computers, are exempted from this regulatory act and hence they don't have to worry about the disposal problem. The Toxicity Characteristics Leaching Procedure (TCLP) test determines whether the waste generated is toxic or not. If the toxic characteristic exceeds certain threshold for various constituents including metals, i.e. lead, cadmium, in the TCLP test, then these constituents are treated as toxic materials. The main toxic substance of concern in CRT's is lead, which fails the TCLP test and so cannot be landfilled without certain prior processing.

Though consumers are aware of environmental conscious products, most of them do not pursue the environmental risks that follow the disposal of the product. So, public education and awareness should be undertaken to convey this problem to the consumers. Logistical factors contribute to difficulties in large scale collection and processing of televisions. So, recycling of televisions becomes less efficient and economical than other commercial or industrial products due to its diversity and difficulty in collection. Also, demanufacturing is currently a low technology process consisting mainly of manual disassembly and visual identification of materials, which leads to inefficient processing of various television types. The dispersion of these products over a wide geographic area also complicates and increases the cost of collection. And so the development of an infrastructure to effectively encourage large scale recycling needs to be undertaken.

CHAPTER 5

INVENTORY ANALYSIS

5.1 Introduction

This chapter introduces a procedure for conducting inventory analysis of metals and glass used in any electronic product and particularly for CRT's. In the metals industry, creative, efficient, and cost effective methods are needed to address the environmental issues that are known and those that are just beginning to be recognized. Materials along with energy are fundamental to the life cycle assessment of any manufactured product. The most effective approach to deal with complex and pervasive environmental issues is to utilize lifecycle analysis.

Hence, the study done here is based on the inventory analysis concept, which has been the best drafted and structured component of LCA. The component of lifecycle inventory analysis for product materials concentrates on quantifying the raw material requirement and associated environmental burdens for the entire lifecycle of a product. The quantification of process materials, energy use, and environmental impact for extraction of raw materials themselves is also of importance and hence is emphasized in this thesis chapter. A generic model for primary production of any raw material is developed and described in subsequent sections. This model is different from that explained in the methodology chapter, which is more applicable on a systems basis. This model is more specific to the production of raw materials from mining to the preparation of the feedstock.

5.2 Role of Materials in MLCA

Industrial materials play a significant and determining role in the outcome of MLCA studies performed on any manufactured products, packaging, and buildings. Whether they be steel, aluminum, copper, lead, plastic, or glass, materials are analyzed at each of the lifecycle stages. Moreover, materials production is, itself, one of the generic lifecycle stages, and “raw materials” is one of the main categories of inputs in the MLCA framework.

At other lifecycle stages, product manufacturing is affected by input materials, their composition and processing characteristics; product use is directly related to materials performance and properties; and at the end-of-life stage, product disposal is usually characterized in terms of waste materials recovery and processing, termed as re-engineering in MLCA.

Similarly, at the process level, materials may enter the system either in the main production or as catalysts or other process ancillaries. In all these steps energy plays a fundamental role both in the main lifecycle sequence and as an input to materials production processes. So, performing lifecycle inventory analysis of raw materials is important for two general reasons. Firstly, it is pertinent on a stand-alone basis as one tool in the environmental evaluations of materials. Secondly, materials information forms part of the analyses that would constitute a full LCA study for a product [26].

In the multi-lifecycle assessment of products, *materials information* is necessary wherever materials are used in manufacturing, in products, or needed as ancillary inputs; hence materials data are necessary to an Lifecycle Inventory (LCI) and to a full MLCA. Product manufacturers have realized that materials are directly linked to the application of the LCA method and that their products will be affected by decisions arising from the LCI of materials.

5.3 Methodology Overview for Conducting LCI

Since materials fit directly into only a portion of the LCA framework, lifecycle analysis of the production of a material results in a material eco-profile and hence covers only the stages in the lifecycle relevant to materials production. This leads to several material related alternatives for improvement in decisions arising out of the use of a full LCA study.

The main aim is to reduce the environmental impacts over the entire lifecycle including reductions of resource requirements, pollution and wastes. As many materials are produced from alternative production rules, their eco-profiles would be significantly different but the major differences will be extrinsic to the material itself. Also, many metals come from mixed ores, which raises the issue of co-product allocation. So, in any LCI study for materials, there has to be an explicit and transparent selection and execution of allocation rules, which has been discussed in the system boundaries section. The approach used in this LCI study is consistent with the general principles of LCA described in the methodology chapter.

In this study, five materials – steel, aluminum, copper, lead, and leaded glass were examined. Many stages and interrelations can be identified for industrial systems in terms of flows of material and energy from unit process to unit process. Energy, process materials, and transportation are necessary physical inputs for most of these stages, and feedback and loops make up part of the cycle. Though it is necessary to distinguish the acquisition and production of energy carriers in a distinct analysis, they are not considered in this study. Energy profiles were used only as input information to the various stages of material production. The lifecycle inventory was limited to the stages of material production only and inventory and impact of process materials required for these production stages were not considered. This constraint made the LCI more manageable to focus on unit production processes whose inputs and outputs can further contribute significantly for an environmental impact study. For each of the metals discussed, specific methodological consideration, assumptions and other details are discussed. A common procedure was followed for conducting the LCI in the form of a generic process model, which is described later.

Thus, the analysis of each of the five materials consists of the following components:

- Basic initial data about the material,
- A brief description of the major production process,
- Construction of the generic process model for the material in terms of production process flow chart, which indicates the major raw and process materials and unit processes with quantitative energy and environmental values for the unit operations,
- A detailed inventory chart indicating the amount of raw and process materials and the total energy requirement, and
- Environmental impact issues associated with the production of the materials.
- Notes and references, which indicate the sources used to develop the generic model in the inventory chart.

5.3.1 System Basis and Boundaries

The basis of a model system is the unit of measure against which all other quantities are assessed [26]. For each of the metals described here, a one ton basis was used. For energy forms a standard unit of energy was used {Mega Joules (MJ) for process heat, Million British Thermal Units (MBTU) for other fuels used, and KiloWatt Hour (KWh) for electric power).

The quality of a lifecycle inventory analysis depends on an accurate description of the system to be studied. Data required for collection and results interpreted from outputs of the analysis are subject to which inventory is being analyzed and where each lifecycle stage starts and ends. Hence, a system boundary must be defined.

The inventory analysis generally includes energy consumption, waste emissions and process material requirements at each stage in the production of any raw material. In this study, process materials and energy required for the production of the above mentioned metals will be considered to be inside the system boundary. Materials used to fabricate fundamental equipment and tools as well as those indirectly consumed during the production and operation of a transportation vehicle will remain outside the boundary. Also materials specifically involved in the generation of energy will remain outside the system boundary. Finally, assumptions and adjustments were necessary to simplify the analysis. Generally the limits placed on the breadth and depth of LCA analysis can be classified as restriction on (1) the lifecycle boundaries of a system or (2) the actual information collected, whether it is limited in its specificity or number of inventory categories. Co-product allocation being one of the most difficult issues in LCI was considered out of system boundary and scope of this research and thesis.

But, again, it is important to note here that, even if the quantification of co-products is not considered, their qualitative aspect is still analyzed. What it essentially means is, in the total LCI study of materials carried out in this research, there are several processes in which the wastes and emissions produced can be used to manufacture a different product altogether called as a co-product or by-product of that process. So, this research only identifies the possible manufacture of by-products in a particular process. The terms co-product and by-product are used inter-changeably and the technical meaning of co-product is defined in the methodology chapter.

5.3.2 Construction of Generic Process Modeling Structure

The primary production process for each of the materials – steel, aluminum, copper, lead, and leaded glass differs from each other. It was necessary to standardize and develop a generic modeling structure for the production of these materials, which can help in comparing these materials against each other. Figure 5.1 shows this generic process modeling structure developed for production of any material.

The figure shows four basic stages for producing the raw material. Every stage has inputs in terms of the process material and energy required for that particular stage. The first stage is of mining, extraction, beneficiation and other initial processing, which prepares the ore for further processing. The main input to this stage is in terms of the primary ore required for the particular material. Energy associated with the mining and extraction activities is also considered. The output of each stage, until the last, is the primary input for the subsequent stage. Secondary outputs in terms of co-products and residues generated are also indicated.

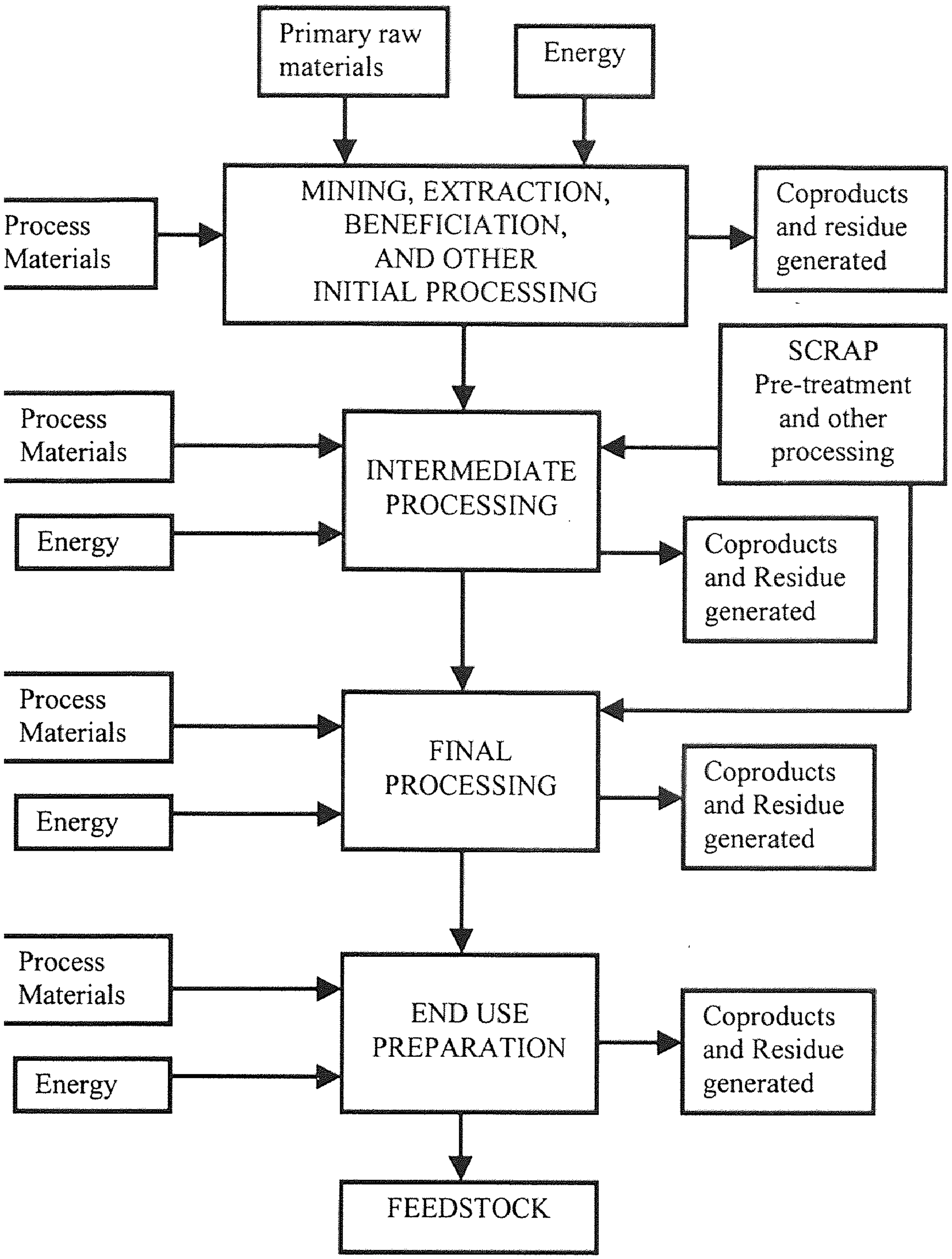


Figure 5.1 Generic Process Modeling Structure

The output of the last stage, referred as the end-use preparation, is the basic feedstock required for the production of any fabricated product – CRT's for this study. The number of stages required for the production of any material are four as per the model and hence is called the generic process model. The model also shows input in terms of scrap. This primarily refers to the secondary production of the same material. The input of scrap, in this model, will differ from material to material. Of course, some initial pre-treatment and processing is required for this scrap to be input in the model. The scrap pre-treatment and processing is usually done at the demanufacturing facility by the demanufacturer. This is what basically makes the *reengineering* process, by which the scrap is sent back either to the smelter or other application user, all the more important and economical. But, again, the quantification of the inputs in this process is not considered in this research.

Once the material to be analyzed is identified, the complete material flow system must be defined to provide a basis for data gathering and calculations. Thus, each stage is recognized as a sub-system of the material flow system. Though, material balance calculations are not provided, the process material requirement at each stage is calculated and indicated in the process flow diagram and also in the inventory chart for each material analyzed.

The subsequent sections describe the LCI analysis for the different materials. The analysis starts with the most common and widely used material – steel. The second is aluminum, followed by copper, lead, and leaded-glass.

5.4 Steel

5.4.1 Basic Initial Data for Steel

There is no single material called as steel; but rather, there are hundreds of steels with varying compositions. They are all basically iron, which is the primary ore required for production of steel, and contain carbon that ranges in different steels from less than 0.1% to 2.0%. But still, the basic production process for all the steels remains the same and hence alloying of steels is considered out of the system boundary, as it does not affect much in the overall LCI for steel. Iron (Fe) is the fourth most abundant element in the earth's crust and ore deposits containing substantially more than the average of 5% Fe are widely dispersed throughout the world [27].

Data has been acquired and analyzed to represent modern production. Due to lack of data in many areas and in the publication of current data the analysis is not a representative of 1997 production. Also, this analysis typifies the range of worldwide practices. The co-products that can be recovered from the steel making process are coke-oven by-products and blast-furnace gas. The upstream boundary starts from the earth, but excludes the production of primary raw materials – limestone and coke, required for the production of pig iron. The downstream boundary is the production of finished steel and does not include any further processing for particular applications such as slab, blooms, etc.

An integrated steel plant is a complex web of materials and energy flows. Within the integrated plant, numerous processes are involved with many inputs and outputs, including co-products. Scrap steel from post consumer and industrial sources is recovered and recycled in both integrated and Electric Arc Furnace (EAF) production, which provides input of steel required for its production. As discussed earlier, only qualitative information regarding the secondary production is considered in this research, and any quantification of secondary production of steel is excluded.

5.4.2 Major Production Process

The production of steel at an integrated iron and steel plant is accomplished using several interrelated processes. The major processes are sinter production, iron production and preparation, steel production and finished product preparation. Each of this processes are described below:

Sinter production: The sintering process converts fine-sized raw materials including iron ore, coke breeze, limestone, mill scale, and flue dust, into an agglomerated product, called sinter, of suitable size for charging into the blast furnace. The raw materials are sometimes mixed with water to provide a cohesive matrix, and then placed on a continuous travelling grate called the sinter strand. The coke in the mixture is ignited initially after which, the combustion is self supporting and provides sufficient heat, 2400 to 2700° F, to cause surface melting and agglomeration of the mix. After taking out from the furnace, the sinter is cooled, crushed and screened for a final time, and sent to be charged to the blast furnace. On an average, 2.5 tons of raw materials, including water and fuel (coke), are required to produce 1 ton of product sinter.

Iron production and preparation: Iron is produced in blast furnaces by charging through its stock iron as ore, pellets and/or sinter, flux as limestone, dolomite and coke for fuel. Iron oxides, coke and fluxes react with blast air to form molten reduced iron, carbon monoxide (CO) and slag. The byproduct gas is collected through offtakes located at the top of the furnace and is recovered for use as fuel. The production of one ton of iron requires 1.4 tons of ore or other iron bearing material; 0.5 to 0.65 tons of coke; 0.25 tons of limestone or dolomite; and 1.8 to 2 tons of air. By-products consist of 0.2 to 0.4 tons of slag, and 2.5 to 3.5 tons of blast furnace gas containing up to 0.1 ton of dust.

Now, the molten iron produced should be prepared for the blast furnace for steelmaking. This process is usually called as hot metal desulfurization. Here the sulfur in the molten iron is reduced before charging into the steelmaking furnace by adding reagents. The most common reagents are calcium carbide (CaC_2) and calcium carbonate ($CaCO_3$) or salt coated magnesium granules. These reagents are injected into the metal with high pressure nitrogen.

Steel production and finished product preparation: Currently there are two major processes for production of steel – Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF) as described below:

Basic Oxygen Furnace (BOF) – In basic oxygen process, molten pig iron from the blast furnace and iron scrap are refined in a furnace by injecting high purity oxygen. Typically, 70% molten metal and 30% scrap metal are used. Impurities are removed when oxygen reacts with carbon. The reactions are exothermic and so, do not require any external heat for the furnace. Thus a typical BOF cycle consists of the scrap charge, hot metal charge, oxygen blow (refining) period, testing for temperature and chemical composition of the steel, alloy addition and re-blows (if necessary), tapping, and slagging. The full furnace cycle usually ranges from 25 to 45 minutes.

Electric Arc Furnace (EAF) – These are basically used to produce carbon and alloy steels. The input material here is 100% scrap. The furnace is equipped with carbon electrodes and electric current of opposite polarity electrodes generates heat between the electrodes and the scrap. After melting and refining periods, the slag and steel are poured from the furnace by tilting. The cycles here range from about 1.5 to 5 hours to produce carbon steel and from 5 to 10 hours to produce alloy steels.

After steel has been tapped from these furnaces, it is poured into ingots, which are later heated and formed into other shapes such as slabs, blooms, or billets.

Secondary production of steel: The secondary production of steel is essentially the same as the steel produced in the Electric Arc Furnace, because in an EAF all the input material that is used is steel scrap obtained from different sources. But the scrap obtained from these various sources contains impurities and should be pre-treated and cleaned. Thus, the secondary production of steel is not separately shown in the generic modeling structure of steel, as it is the same as the primary production, with the difference that Electric Arc Furnace is used instead of Basic Oxygen Furnace. Due to this, the environmental burdens of mining and production of other process materials such as coke, iron, and limestone are reduced.

5.4.3 Construction of Generic Process Model for Steel

After, studying the entire primary and secondary production process of steel, a generic process model was developed. The model essentially identifies the various steps of primary and secondary production, taking into consideration the system upstream and downstream boundaries. It also indicates the amount of raw and process materials required at each stage of the production. The energies are also accounted for and indicated. The energies are separated into two categories namely process heat required in Million British Thermal Units (MBTU), fuel required in Mega Joules (MJ), and other category is the amount of electricity required in Kilowatt hours (KWh).

The generic process model for production of steel is shown in figure 5.2. The actual numbers for the raw and process materials are given in the inventory chart.

5.4.4 Detailed Inventory Chart for Steel Production

Though the generic process model gives the quantification of inputs and outputs at every stage of the production process, it is still necessary to develop a inventory chart which gives a quick review of the production inventory. Also, this chart indicates the total energy requirements for the entire production process from ore mining to the forming of metal defined in the downstream boundary. Moreover, other wastes, emissions, or water effluents not shown in the model are accounted for in this chart.

Table A.1 in Appendix A show the inventory chart for steel production. The inventory for secondary steel production is out of the system boundary and hence not considered.

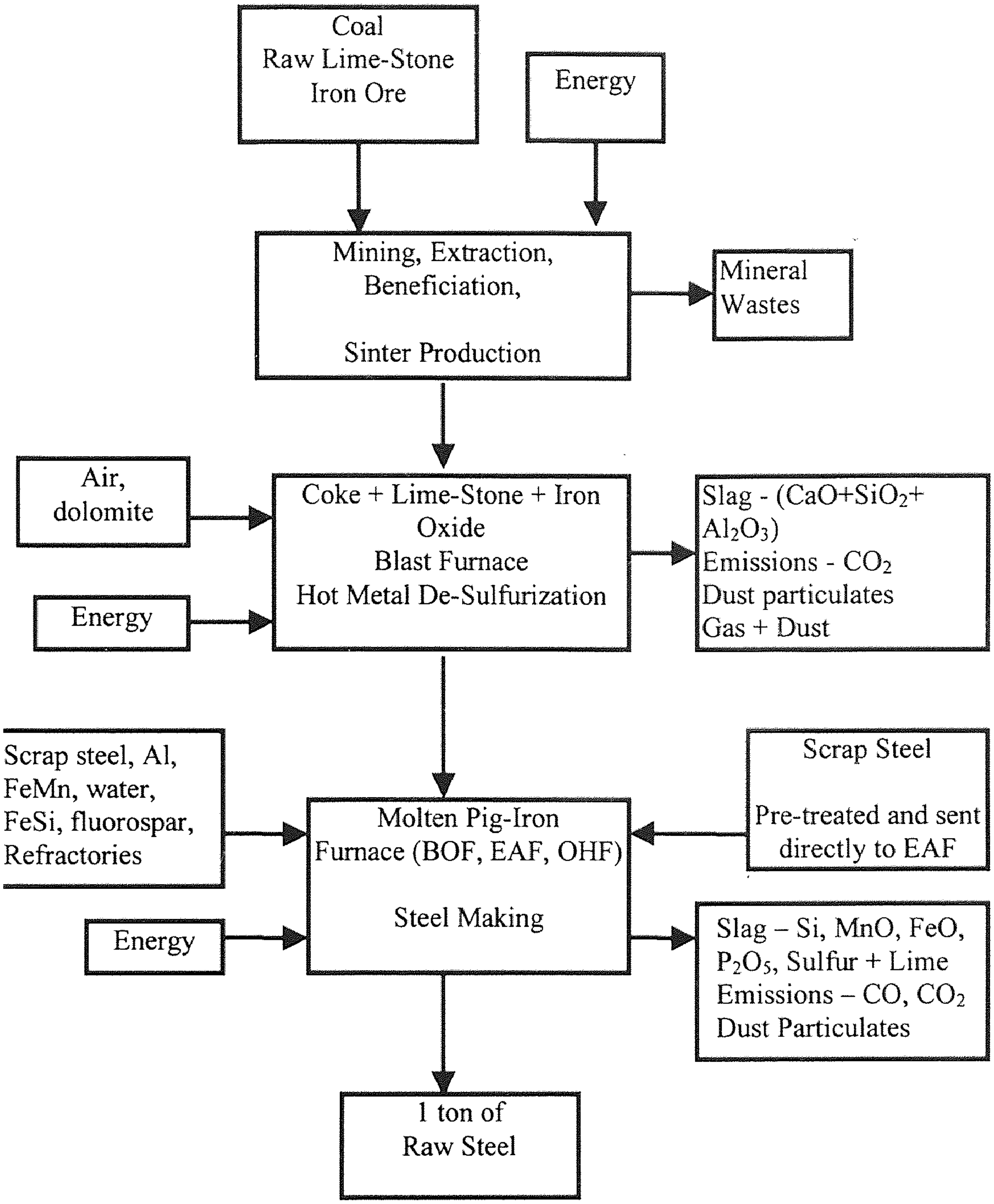


Figure 5.2 Production of Steel

5.4.5 Environmental Impact Issues

In terms of the Gross Energy Requirements (GER) for an integrated iron and steel plant, half the energy can be traced directly to the use of coke in the blast furnace and, subsequently, to the coking coal requirement. The remaining 50% is almost equal to other fuel inputs and the electric power requirement. Thus, fuel in the form of coke and natural gas is consumed more than the electricity, which should be concern in the light of reducing natural resources. The comparison of the gross energy requirements between the materials analyzed in this thesis is shown in the summary of inventory analysis section of the conclusion chapter.

The combustion of fossil fuels required for production of iron-ore, limestone, coke, and also for steel production contribute strongly to the green house emissions. The balance of Global Warming Potential (GWP) arises from the integrated plant due to its fuel and electric power inputs. There are other processes, such as transportation, which contribute to GWP as a result of their carbon dioxide and nitrogen oxide emissions.

Slags and solid wastes are produced at every stage of production, because of the fact that no process is 100% efficient. To maintain the material balance across the entire production of steel quantifying and assessing these wastes. In an integrated iron and steel plant most of the solid waste is associated with the production of the raw materials itself. Other solid wastes and slags are in the form of ash, and air pollution control waste. The characterization and categorization of these wastes and slag's as by-products is uncertain and depends upon the manufacturer.

5.4.6 Notes and References

There are several dimensions to the LCI conducted for steel in this research. The inventory generated is based on secondary data derived mostly from statistical and generic process records. This kind of analysis can both be strength and weakness, because generic results can be appropriately used in a broad analysis to compare different materials in a general manner. However, due to the non-specificity of the inventory data to any particular plant neither detailed recommendations nor targeted conclusions can be derived.

The data in terms of production processes and actual quantification of the inventory numbers is derived from various reliable and quality sources. There is no single data source or manual from which the inventory chart is compiled. The main data sources in generating the inventory chart and the generic process modeling structure are: Ph.D dissertation of Dr. Steve Young [26], Battelle report on "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing"[30], LCA of Building Frame Structures by International Iron and Steel Institute (IISI) [31], and Environmenatal Protection Agency, "Sector Note-books for the Iron and Steel Industry" [29].

The actual inventory numbers for the steel were not that difficult to gather, as there is published data available on steel from a variety of sources indicated above. Also, the International Iron and Steel Institute (IISI) is conducting a complete Lifecycle Analysis of steel and it should be available in near future.

5.5 Aluminum

5.5.1 Basic Initial Data

Aluminum is the most abundant metal in the earth's crust, making up almost 8% of the total volume. Bauxites are the principle ores of alumina and although they vary greatly in appearance and composition, they are all mixtures of hydrated aluminum oxides with impurities in element [28].

Aluminum ranks second, only to steel in total production of metals, with annual global primary production of almost about 20 million tons (Mt) [26]. Aluminum competes with steels and plastics for mechanical applications and with copper for thermal and electrical applications. The scale and expanse of aluminum production is large and important in its inventory analysis. With growing resource and environmental concerns, the metal has become one target of ecological concern and also, in the light of sustainable development, the environmental evaluation of aluminum production is topical and relevant. As new approaches emerge for pollution prevention, use of aluminum and other materials will be of significant issue [26].

The production process described and the inventory generated is not specific to any particular facility, but is an average for global production of primary aluminum, since major production processes are relatively consistent around the world. The upstream boundary is defined as the ore in the ground, which is the basic raw material for production. The downstream boundary is defined as the metal coming out of the Hall-Heroult or the refining process. The alloying additives were excluded from the system boundary.

5.5.2 Major Production Process

Aluminum production basically consists of four major steps: mining, refining the bauxite into alumina (Bayer process), smelting the alumina into aluminum (Hall-Heroult Process), and final processing into specific feedstock specifications.

Mining: Most bauxite lies near the surface of the earth in open pits where it is surface mined. It is then crushed, ground, and kiln dried to remove excess moisture. Overburden is removed at a ratio of about three tons to one ton of ore.

Refining (Bayer Process): The method used to separate alumina from impurities in the bauxite is called the Bayer Process. In this process, bauxite is dried, ground in hall mills, and mixed with caustic soda and digested under heat and pressure. This dissolves the alumina in the bauxite in the caustic soda to form sodium aluminate, leaving behind the impurities as insoluble solids which are filtered out in a series of pressure reducing tanks and filter presses. A flocculent, such as starch, is added to increase the settling rate of the red mud. The solution containing alumina is cooled and seeded with fine crystalline alumina hydrate to precipitate alumina trihydrate, which is then filtered, washed, and heated in kilns to drive off chemically attached water and yield commercially pure alumina. The dry alumina is then shipped to the aluminum smelter. The main slag from the Bayer process is the red mud, which is about two tons per ton of solid metal produced.

Smelting (Hall-Heroult Process): Crystalline alumina (Al_2O_3) obtained from the above process is used in the Hall-Heroult process to produce aluminum metal. This is the most common process for producing aluminum. Electrolytic reduction of alumina occurs in shallow rectangular cells or pots, which are steel shells lined with carbon. Carbon electrodes extending into the pots serve as anodes, and the carbon lining as the cathode. Molten cryolite (Na_3AlF_6) functions as both the electrolyte and the solvent for the alumina. The electrolytic reduction of Al_2O_3 by the carbon from the electrode occurs as follows:

$$2\,Al_2O_3 + 3C \longrightarrow 4Al + 3CO_2$$

Aluminum is deposited at the cathode, where it remains as molten metal below the surface of the cryolite bath. Aluminum product is tapped every 24 to 48 hours beneath the cryolite cover, using a vacuum siphon. The metal is then transferred to a reverberatory furnace, where it is alloyed, fluxed and degassed to remove trace impurities. It is then transported to fabricating plants.

Emissions from the cells include CO_2, CO, NO_2, SO_2, various hydrocarbons and fluorinated gases. Approximately 580 kgs of carbonaceous consumable anodes and cathode potliners are consumed per ton of aluminum smelted, contributing energetically to the reaction [26]. Nitrogen oxides are produced at a level that is negligible in the overall inventory.

The manufacture of electrodes themselves is considered out of system boundary and hence emissions from them are not reflected in the inventory. Spent potliner solid wastes are produced at a rate of about 20kg/t metal, which primarily consists of expanded carbonaceous cathodes and contains carious species, including cyanide [26].

Secondary aluminum production: Due to the higher energy requirement and cost of primary production, secondary sources of aluminum contribute significantly, to about 30% of total metal production [26]. Recycling of aluminum has been considered very successful over the years and hence scrap recovery is actively encouraged and supported.

There are three kinds of scrap: old scrap from post-consumer resources like automobiles and beverage cans; new scrap is from manufacturing plants; and mill scrap from aluminum casting and finishing operations. But the last does not contribute to secondary production as it is contained within the finishing stage of primary production [26].

Secondary aluminum production involves two general categories of operations, scrap pretreatment and smelting / refining.

Scrap Pretreatment: Aluminum scrap pretreatment involves sorting and processing of scrap to remove contaminants and to prepare the material for smelting. Sorting and processing separates the aluminum from other metals, dirt, oil, plastics, and paint, by cleaning process based on mechanical pyrometallurgical, and hydrometallurgical techniques. Painted scrap requires delacquering before metallurgical processing.

Smelting/Refining: This primarily takes place in a reverberatory furnace. The melting furnace is used to melt the scrap and remove impurities and entrained gases. Smelting and refining operations usually involve the following steps: charging, melting, fluxing, demagging, degassing, alloying, skimming, and pouring. These processes vary and hence are not discussed here. The secondary production is considered just for the sake of completeness and hence its inventory is not calculated and is out of scope of this research.

5.5.3 Construction of Generic Process Model for Aluminum

The construction general of the model for aluminum is similar to that for steel. The main difference is the flow of scrap for secondary aluminum production in the generic process for primary production. After, pre-treatment of the scrap, as discussed in the secondary production process, the aluminum scrap enters the generic model at the final processing stage for primary aluminum production. This in itself shows the economics behind aluminum recycling. Aluminum recycling has become a very profitable and environmentally benign way of treating aluminum scrap, which can be clearly understood by analyzing the generic process model for aluminum production.

Figure 5.3 shows the generic process model for the primary and secondary production of aluminum.

5.5.4 Detailed Inventory Chart for Aluminum Production

The explanation and analysis of the inventory chart development is the same as for steel and hence not discussed again. Table A.2 in Appendix A shows the detailed inventory chart for primary aluminum production process. All the quantities indicated are in tons and the fuel energy in Giga Joules (GJ), and the electricity KWh.

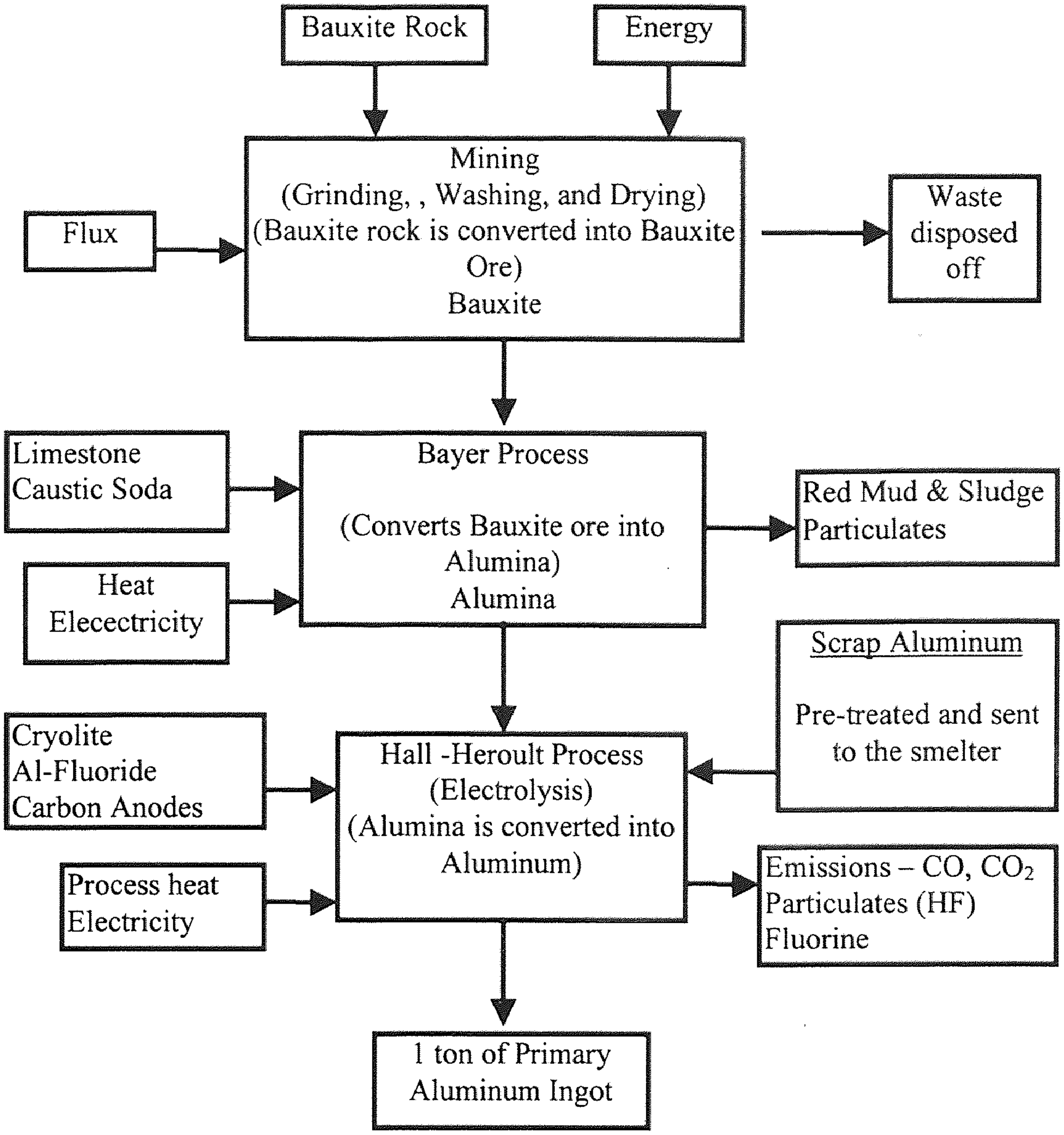


Figure 5.3 Production of Aluminum

5.5.5 Environmental Impact Issues

The main element in the Gross Energy Requirements (GER) of primary aluminum production is the electric power for the smelting operation. Some 65% of gross energy and 95% of total electric power is required in smelting of primary aluminum [26]. Energy required in the Bayer process is basically in terms of fossil fuels. Secondary production of aluminum requires only 5-7 % of virgin or primary production of aluminum.

There are considerable amounts of perfluorocarbon (PFC) emissions during aluminum production. These will greatly affect the GWP indicator profile if calculated. There are other important emissions such as carbon dioxide and carbon monoxide emissions. But, PFC's contribute to 50% of the total GWP [26] and hence should be addressed and taken care of. Other emissions are comprised of carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), fluorides, and particulates. Controls are currently required to minimize emissions of fluorides and particulates and these controls generally recycle the captured pollutants back to the process. For aluminum, it is very important to note that much of the energy is provided by hydroelectric power, which produces no greenhouse emissions.

The main solid waste in aluminum production is the "red mud", which is produced during the refining operation. The total amount of red mud along with sludge generated during the alumina production is considerable and is around 1.9 tons per ton of aluminum produced. The smelting wastes are usually dross and spent potliners, which poses problems due to the presence of polycylic aromatic hydrocarbons (PAH) and cyanide in them. But most of the solid wastes are recycled back into the primary production process of aluminum. The wastes generated may be either hazardous or non-hazardous. Hazardous and non-hazardous solid wastes are sent to approved landfills.

5.5.6 Notes and References

Like steel, the inventory data is not specific to any facility, but largely an average of data gathered from different sources. The GER for secondary aluminum production are considerably lower than the primary production. The GER for both of these are included in the inventory chart.

The data required for the inventory of primary production was mainly gathered from: Pollution Prevention in the Aluminum Industry, a project by Aluminum Companies Association [32], Ph.D dissertation of Dr. Steve Young [26], Battelle report on "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing" [30], Industrial Ecology – Towards Closing the Materials Cycle [33], EPA sector note-books for Non-Ferrous Industry [34].

5.6 Copper

5.6.1 Basic Initial Data

The United States is the largest producer of copper, and obtains about 1.25 million tons annually from various mines in the entire country. Copper ore is produced in the U.S. and in 1989, Arizona produced 60% of the total U.S. ore. Copper in the U.S. is produced primarily by pyrometallurgical smelting methods, which use heat to separate copper from copper sulfide ore concentrates.

The most common ore of copper is chalcocite (C_2S). It contains one-third each of copper, sulfide, and iron. More than 20 other copper ore minerals are known, but only enargite (sulfursenide, 48.3% Cu) and the less abundant covellite, tetrahedrite, atacomite, and famatinite, are commercially valuable in a few mines. Many copper mines contain some zinc, lead, arsenic, cobalt, and small, but valuable, amounts of gold and silver.

The upstream boundary starts from mining of the ore from the earth/open-pit mines. The downstream boundary is limited to the production of a ton of copper cathode, and further processing of copper is not considered. Again, transportation at all levels is excluded from the inventory data. It is important to note here that all pyrometallurgical processes are not strictly comparable (i.e. the iron in the concentrate ends up as sulfuric acid) [35]. But, co-product allocation is excluded from this study and hence sulfuric acid production from sulfur dioxide emissions is not given any credit in energy balance. But if such credit were allowed (on basis of comparing this sulfur against fresh sulfur), the energy per ton of cathode copper would decrease by about 6% but a similar credit would have to be given again to these processes producing sulfuric acid or liquid SO_2 [35].

5.6.2 Major Production Process

The major steps involved in the production of copper are: mining, concentration, roasting, smelting, converting, and finally fire and electrolytic refining. For the purpose of this research and to accommodate the production process of primary copper in the generic modeling structure, the mining, concentration and roasting operation are considered in the same unit process termed as initial processing. But, all the inputs in terms of process materials and outputs in terms of slag and emissions are considered for all the unit operations. Energy calculations are done on a total basis and energy values indicated are the combined energies for the three operations in both the mining, initial, and the intermediate processing unit processes. The detailed process descriptions are as follows:

Mining, concentration and roasting operations: Mining produces ores with less than one percent copper and hence concentration is required. It is accomplished by crushing, grinding and flotation purification, resulting in ore with 15 to 35% copper. The flotation process separates the concentrated ore into fractions, which are then dewatered by clarification and filtration, resulting in 10 to 15 percent water, 25 percent sulfur, 25 percent iron, and varying quantities of arsenic, antimony, bismuth, cadmium, lead, selenium, magnesium, aluminum, cobalt, tin, nickel, tellurium, silver, gold, and palladium.

In roasting, charge material of copper concentrate mixed with a siliceous flux (often a low-grade copper ore) is heated in air to about 1200 F, eliminating 20 to 50 percent of the sulfur as sulfur dioxide (SO2). Portions of impurities such as antimony, arsenic, and lead are driven off, and some iron is converted to iron oxide. The roaster has self-generating energy by the exothermic oxidation of hydrogen sulfide, as shown in the reaction below:

$$H2S + O2 \longrightarrow SO2 + H2O + \text{Thermal Energy}$$

The copper obtained after roasting is called as calcine, which is then sent to the smelter.

Smelting, converting, and fire-refining operations: In the smelting process, either hot calcine from roasted or raw unroasted concentrate is melted with siliceous flux in a smelting furnace to produce copper matte. The required heat comes from partial oxidation of the sulfide charge and from burning external fuel. The slag obtained is in the form of iron and some other impurities. The copper matte ranges from 35 to 65 percent copper. There are four major types of smelting furnace technologies used in the U.S namely, reverberatory, electric, noranda, and flash.

Converting produces blister copper by eliminating the remaining iron and sulfur present in the matte. Copper matte, siliceous flux, and scrap copper are charged in a convertor, by blowing air, or oxygen-rich air. Iron sulfide oxidizes to form iron oxide (FeO) and SO2. A final air blast oxidizes the copper sulfide to SO2, and blister copper forms, containing 98 to 99 percent coppers. The SO2 produced throughout the operations is vented to pollution control devices, and subsequently used to produce sulfuric acid as a by-product, by most smelters.

The blister copper still may contain impurities in the form of gold, silver, antimony, arsenic, bismuth, iron, lead, nickel, selenium, sulfur, tellurium, and zinc. The first step to remove these is the fire-refining of blister copper. In fire-refining, blister copper is usually mixed with flux and charged into the furnace, which is maintained at 2010 F. Air is blown through the molten mixture to oxidize the copper and any remaining impurities, which are removed as slag. The remaining copper oxide is subjected to a reducing atmosphere to form purer copper, and then cast into anodes for even further purification by electrolytic refining.

Electrolytic refining: This is the final processing step in the generic modeling structure for copper. Here copper is separated from impurities by electrolysis in a solution containing copper sulfate (Cu2SO4) and sulfuric acid (H2SO4). The copper anode dissolves and deposits at the cathode, to form 99.95 to 99.96 percent pure copper cathode, which is then cast into bars, ingots, or slabs. During the process, the copper anode dissolves, and metallic impurities precipitate and form a sludge, which is then processed to recover noble metals like gold, silver, etc. Again, these are not accounted for in the inventory analysis as by-products and hence no allocation made.

Secondary copper production: As of 1992, more than 40 percent of the U.S supply of copper is derived from secondary sources, including such items as machine shop punchings, turnings, and borings; manufacturing facility defective or surplus goods; automobile radiators, pipes, wires, bushings, and bearings; and metallurgical process skimmings and dross. Secondary copper production essentially consists of four separate operations: scrap pre-treatment, smelting, alloying, and casting.

Scrap Pre-treatment – The scrap is separated from other impurities either by manual, pyrometallurgical, or hydrometallurgical methods. All these methods basically clean the scrap and makes it ready for the smelting furnace.

Smelting – The low-grade copper obtained from the scrap pre-treatment process is melted in a blast or rotary furnace to obtain slag and impure copper. Remaining processes are essentially the same as primary production of copper. Hence in the generic modeling structure specific to copper, the secondary copper production is shown as pre-treated scrap entering at the intermediate unit processing step. The point to emphasize here is the savings in energy and raw materials achieved due to the secondary production of copper which enters the primary copper production process at the second stage, thus reducing the first step (mining, concentration, and roasting) burdens over the entire production process of copper.

5.6.3 Construction of Generic Process Model for Copper

Again, the discussion for developing the generic process model for copper is similar to that for steel, and aluminum and hence it is not explained. Figure 5.4 shows the generic process model for the production of copper from its ore.

It is indicated in the generic process model for copper that copper ores have very less concentration of copper (0.76 %), and hence mining and beneficiation of copper from copper ores is a costly operation.

5.6.4 Detailed Inventory Chart for Copper Production

The explanation and analysis of the inventory chart development is the same as for steel and aluminum and hence not discussed again. Table A.3 in Appendix A show the detailed inventory chart for primary copper production process.

As stated above that copper ores have very less concentration of copper, can be verified by the amount of slag generated in the form of tailings, during the mining, beneficiation, concentration, floatation, leaching and roasting process. The total tailings generated are around 160.7 tons per ton of copper produced.

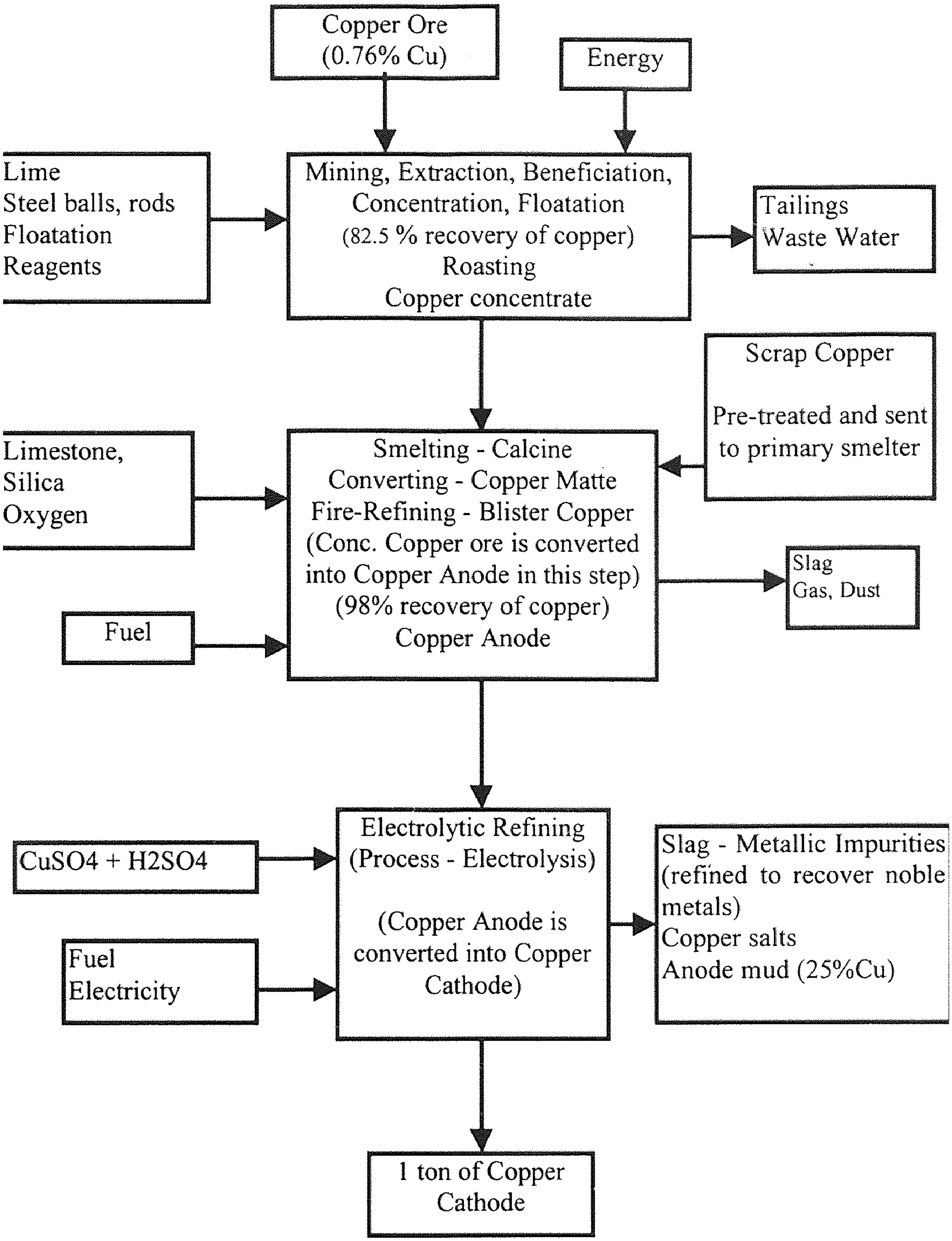


Figure 5.4 Production of Copper

5.6.5 Environmental Impact Issues

In terms of the Gross Energy Requirements (GER) for copper, the mining and beneficiation energy requirements are much higher than other operations, mainly due to the low grade of copper ores and strict environmental controls. Electricity is the major form of energy for copper mining and beneficiation. Moreover, the quality of grades is becoming lower day by day and hence, the mining and beneficiation costs and energy is prone to rise. According to a paper by the Copper Development Association (CDA), if the average grade of domestic ore were to drop to 0.2% copper by the year 2000, nearly 60 million BTU would be required to mine each ton of copper. And this would raise the total energy consumption by an estimated 135 trillion BTU per year at that time [36]. In contrast to this, the secondary copper production requires only one-third to one-seventh of the energy needed for primary production, re-engineering the scrap copper from different sources is a sensible approach to reduce the GER for copper production.

Emissions from the copper production are principally particulate matter and sulfur oxides (SOx). Sulfur dioxide emissions are generated at every stage, except mining, of copper production process. Many smelters recover these emissions in the form of sulfuric acid as a by-product and thus reduce the total amount of emissions to the environment. Other particulate matter contains oxides of copper, iron, arsenic, antimony, cadmium, lead, etc. but are in little amounts and hence are assumed to be less significant.

The solid wastes generated at each stage are in considerable quantities. At the intermediate processing stage total amount of slags and solid wastes generated is almost three tons per ton of copper anode produced. But, most of it is usually recycled back into the process. Slag generated at the refining stage is mainly metallic impurities in the form of noble metals such as silver, gold, etc. So, these are usually by-products and hence make the copper production process more economical. There is anode mud that is generated, but is recycled back as it contains 25% copper.

5.6.6 Notes and References

Again, like steel and aluminum, the inventory data is not specific to any facility, but largely an average data gathered from different sources. The data required for the inventory of primary production was mainly gathered from: Report on "An Assessment of Energy Requirements in Proven and New Copper Processes" [35], Battelle report on "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing" [30], Industrial Ecology – Towards Closing the Materials Cycle [33], and EPA sector note-books for Non-Ferrous Metals Industry [34].

5.7 Lead

5.7.1 Basic Initial Data

Lead is present in the earth's crust to the extent of only about 0.002%, but it is concentrated in various parts of the world in deposits rich enough to warrant mining. Total world consumption of lead is three million tons annually, a large proportion of which is recovered from scrap [28].

Though lead metal not used directly in a CRT, it is used in considerable amounts in the three types of glass produced for a CRT, namely the panel, the funnel and the neck. There is lead present in the frit also, but it does not amount for much, compared to the other three. So, the characterization of lead is helpful in the total multi-lifecycle considerations of a CRT.

The most important lead ore is galena (lead sulfide). The upstream boundary is the ore as obtained from the earth, i.e. mining of galena. The downstream boundary is the lead ingot from the final refining process. Again, transportation issues are not considered here. Also, there are several by-products obtained during lead refining. These are not accounted for and hence their benefits are not allocated to the overall lead production. There are basically only four major facilities in the U.S. that process metallurgical lead [37].

5.7.2 Major Production Process

The production of lead involves three major steps: 1) mining, crushing, grinding and beneficiation to produce lead concentrates, and 2) smelting of the lead concentrates to produce lead bullions, and 3) refining the bullion to separate other metal values and remove impurities.

Mining, crushing, grinding and beneficiation: Insofar as possible, lead is separated from other values in an ore as lead concentrates in the beneficiation steps. In the smelter, lead concentrates are mixed with fluxes and recycle products such as dust from collection systems and slag's. The mixture is then pelletized and sintered on a travelling grate furnace to remove sulfur as SO2 and also some of the impurities and values such as arsenic, antimony and cadmium. The sinter produced is then sent for the smelting operation.

Smelting: The sinter is charged to the blast furnace with coke, fluxes and recycled material from associated operations to yield bullion and slag. The bullion contains roughly 85% pure lead and the easily reducible metals that may be present in the sinter, i.e. copper, antimony, arsenic, gold, and silver. The slag contains silicate from the original charge and zinc. If the zinc content of the ore is high enough, the molten slag is treated in a zinc fuming furnace to recover zinc as zinc oxide. The bullion is then subjected to a series of refining operations.

Refining: The first refining operation to remove copper, drossing, is usually performed at the smelter. If antimony, arsenic or tin are present, the decopperized bullion is then "softened" by oxidizing the molten bullion to remove these elements. The softened lead is then treated with zinc dust (Parke's Process) to remove any gold and silver, which may be present as precious metal compounds. The zinc remaining in the desilverized lead is removed in a vacuum dezincing process. If present, bismuth is removed by the "Betterson Process". Calcium and magnesium, remaining after the debismuthizing step, are removed along with traces of zinc, antimony and arsenic in a final refining step, which involves treatment with caustic soda to which sodium nitrate is sometimes added. The lead from all this refining processes is finally 99.99% to 99.999% pure. The detailed information and description of the individual refining processes, like Parke's Process, and Betterton Process are beyond the scope of this research.

Secondary lead production: Secondary lead smelters produce lead and lead alloys from lead-bearing scrap material. More than 60 % of all lead is derived from scrap automobile batteries. Lead produced by secondary smelting accounts for half of the lead produced in the U.S.

Secondary lead smelting includes three major operations as described below:

Scrap Pre-treatment – Scrap pre-treatment is the partial removal of metal and nonmetal contaminants from lead-bearing scrap and residue. This separated lead scrap is then sweated in a gas or oil fired reverberatory or rotary furnace to separate lead from metals with higher melting points. The partially purified lead is periodically tapped from these furnaces for further processing in smelting furnaces or pot furnaces.

Smelting – Smelting produces lead by melting and separating the lead from metal and nonmetallic contaminants and by reducing oxides to elemental lead. Smelting is carried out in blast, reverberatory, and rotary kiln furnaces. In the blast furnace pre-treated scrap metal, rerun slag, scrap iron, coke, recycled dross, flue dust, and limestone are used as charge materials to the furnace. The process heat needed to melt the lead is produced by the reaction of the charged coke with blast air that is blown into the furnace. Some of the coke combusts to melt the charge, while the reminder reduces lead oxides to elemental lead.

As the lead charge melts, limestone and iron float to the top of the molten bath and form a flux that retards oxidation of the product lead. The molten lead flows from the furnace into a holding pot at a nearly continuous rate. The product lead constitutes roughly 70 percent of the charge. From the holding pot, the lead is usually cast into large ingots called pigs or sows. About 18 % of the charge is recovered as slag, with about 60

% of this being a sulfurous slag called matte. Roughly 5 % of the charge is retained for reuse, and the remaining 7 percent of the charge escapes as dust or fume.

Refining – Refining and casting the crude lead from the smelting furnaces can consist of softening, alloying, and oxidation depending on the purity or alloy type desired. Refining furnaces are used to either, remove copper and anitmony for soft lead production, or to remove arsenic, and copper, and nickel for hard lead production. Sulfur may be added to the molten lead bath to remove copper. Copper sulfide skimmed off as dross may subsequently be processed in a blast furnace to recover lead. Aluminum chloride flux may be used to remove copper, antimony, and nickel. Oxidizing furnaces, either kettle or reverberatory units, are used to oxidize lead and to entrain the product lead oxides in the combustion air stream for subsequent recovery in high efficiency baghouses.

5.7.3 Construction of Generic Process Model for Lead

The discussion for developing the generic process model for lead is similar to that for steel, aluminum, and copper. Figure 5.5 shows the generic process model for the production of lead from its ore.

5.7.4 Detailed Inventory Chart for Lead Production

The explanation and analysis of the inventory chart development is the same as for steel, aluminum, and copper and hence not discussed again. The lead inventory chart is not complete due to lack of data on the emissions and the solid waste side. Considering the time frame of the research and the availability of good quality data, this is not really a drawback. Primary lead production is supplementary to the leaded-glass production, which is of prime focus. Table A.4 in Appendix A show the available detailed inventory chart for primary lead production process.

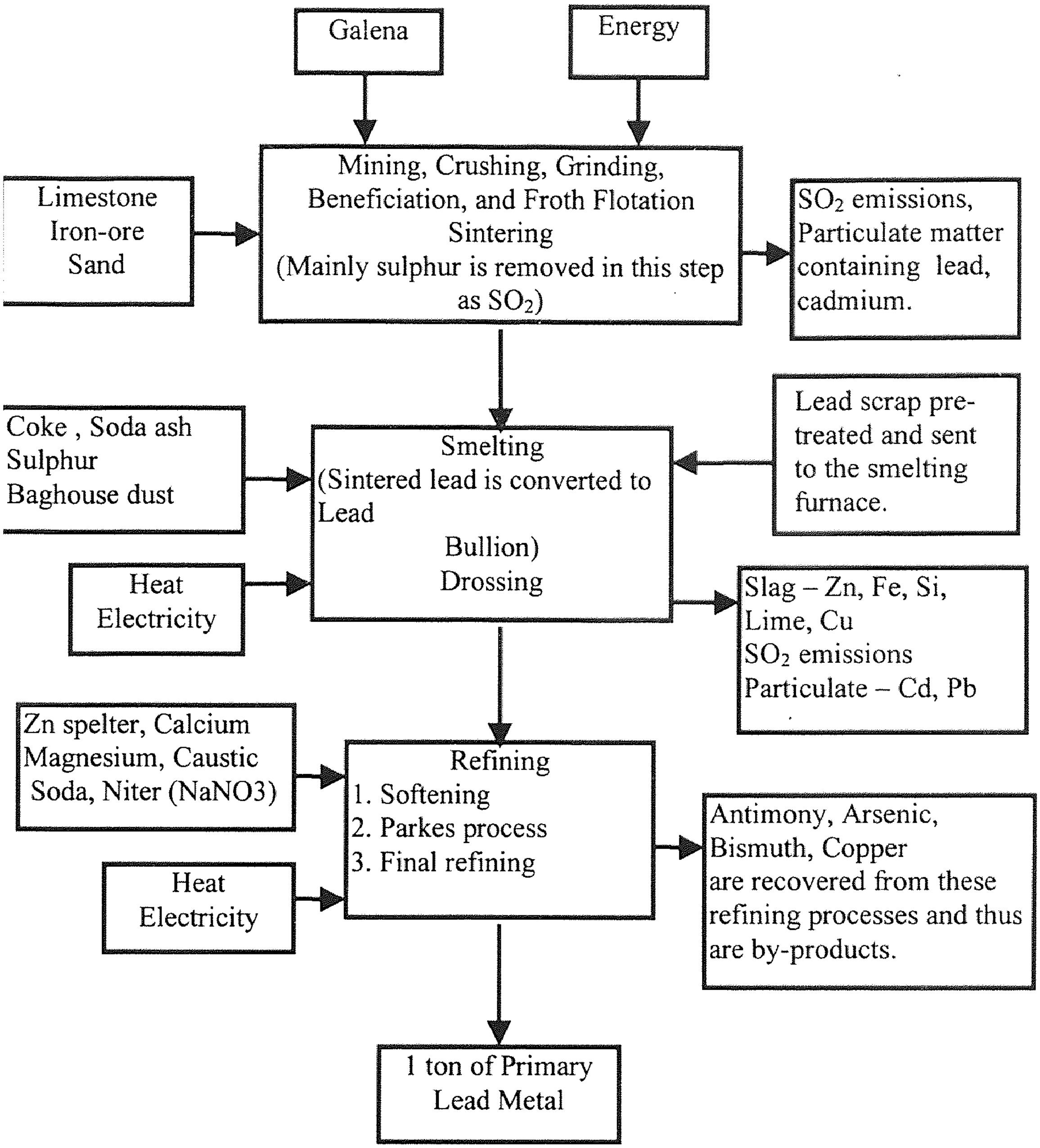


Figure 5.5 Production of Lead

5.7.5 Environmental Impact Issues

The GER for lead production is less compared to aluminum and copper. Though, lead ore is less in extent in the earth's crust, it is concentrated in various parts and hence energy for mining of lead is comparatively low. Again, secondary production of lead consumes less energy than primary and so the lead scrap must be effectively utilized, which also lowers the overall environmental burdens.

The emissions from primary lead production are basically sulfur dioxide (SO2) and other particulate matter. There are some fugitive emissions, mainly from the mining area. But the major area of concern in the production of lead is the emissions of lead itself, which may harm human health and the environment in general, as described in the environmental impacts of CRT section of chapter 4. There are various concerns regarding this and the lead smelters have to abide by strict regulations regarding the amount of lead in the blood of workers in the smelting facility and people living in the surrounding vicinity.

The solid wastes generated from lead production are mainly the impurities, as they are refined from the lead ore. But, these wastes (impurities) are processed further to recover precious metals, like gold and silver and thus are the by-products of the lead production process. Other important environmental problems associated with lead smelting are acid mine drainage, and leaching of toxic heavy metals from mine tailings.

One important note to make here is the environmental concerns and issues that regulate and control the lead industry. Many researchers have studied lead and published many articles related to the environmental impacts of lead mining and production. Since the primary aim here is not to evaluate the impacts of lead industry, the data provided above gives a fairly good overview of the impact that lead has over the lifecycle of a cathode ray tube.

The available data for primary lead production and some for secondary lead production is collected mainly from these sources: Battelle report on "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing" [30], EPA sector notebooks for Non-Ferrous Industries [34], and Journal of Metals Handbook [28].

5.7.6 Notes and References

The data for the production of lead was mainly gathered from Battelle Columbus Laboratories report on "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4 – Energy Data and Flowsheets, High Priority Commodities)," [30] and from a lead oxide manufacturer.

5.8 Leaded-Glass

5.8.1 Basic Initial Data

Leaded-glass has been used in the panel, funnel, frit, and the neck of the CRT since a long time. The amount of lead in all the four components is different. The funnel and the neck have the maximum percentage of lead in the entire CRT. The panel has the lowest percentage of lead (0 - 2 %). Nowadays, most manufacturers do not add lead to the panel. Other oxides such as zirconium and barium are used. The basic elements in the production of leaded-glass are lead oxide and silica, which are easily available.

The importance of using lead in the glass for television picture tube is its capability of absorbing x-rays produced during the CRT functioning. If lead is not used in the glass then the x-rays produced would otherwise result in harmful health effects to those watching television or those repairing televisions.

5.8.2 Major Production Process

The production of leaded-glass is a two step process. The three steps are; production of litharge (PbO), and glass furnace operation. The three steps are described below:

Litharge production: The lead metal is not used directly by the glass manufacturer to make the leaded-glass. Usually, the litharge or lead oxide production is carried out at the lead smelter itself in the last refining operation of the lead metal. But smelters may not do that way. In both cases lead oxide is produced, by supplying oxygen over the lead metal in the refining furnace. This process produces lead oxide or litharge.

The production of lead oxide starts with metallic lead (in the form of ingots) in a large melting pot; feeding the molten lead into a barton reactor, which has an agitator that spins molten lead so that it mixes with the oxygen and oxidizes. Then the oxidized lead is passed into a settling chamber. From this process, the product is approximately 70 percent lead oxide and 30 percent free lead. To further oxidize the product, the mixture goes into a furnace. This oxidized product is referred to as litharge. To further process the litharge to produce the type of lead oxide that the leaded-glass industry requires, the litharge is pelletized in a direct-fired furnace.

The traditional method of litharge production has been in a furnace of proprietary design, which is not particularly fuel efficient by modern day glass design criteria. This furnace design is capable of producing molten litharge, suitable for fritting into pure monolithic granules, with virtually no dissolution of refractory or furnace walls, which might contaminate the end product with no-litharge (PbO) phases.

Glass furnace operation: The subject, "Glass Furnace Operations," is a broad one as there are many different types of furnaces and in addition each furnace has its own peculiar characteristics. Glass properties, to a great extent, depend upon its physical nature and its physical nature in turn depends upon the operation of the furnace. For successful operation of the furnace, the raw materials must be proportioned and mixed correctly. No segregation can be allowed to occur during storage or handling. At the same time, the effect of fuel combustion upon the glass that is melted must be thoroughly understood.

When the batch is fed into the tank and melted, it becomes a glassy, transparent mass. It is formed by the inter-reaction of various chemical compounds at high temperatures. This inter-reaction results in the formation of new compounds, which at this high temperature of formation are soluble in each other. The molten glasses produced by the inter-reactions of the various raw materials are not in the form of a homogeneous solution but tend to run in layers forming what is known as cords. These layers must be stirred together to form a homogeneous mass. This is first accomplished by the evolution of gas from the batch during melting and second by convection. The evolution of gas from the batch during melting serves as to effect mixing of the molten glass. The speed at which this gas is released will determine the extent of mixing. This boiling action serves to stir the various solutions.

Glass melted at a higher temperature will have a higher forming temperature and the same glass melted at a lower temperature will have a lower forming temperature. To produce glass with good formability and quality, one must select a melting temperature, which will give a quick melt, thereby producing a vigorous agitation of the glass being formed. This temperature must be maintained regardless of the demand for the glass at the forming end of the furnace. The efficiency of a glass furnace has to be a balance between heat input and quality glass production.

Secondary leaded-glass production: The secondary production of leaded-glass or recycling as it is normally called depends entirely on the percentage of lead in the glass. Because there is different percentage of lead in all the four glass components of CRT, recycling of glass is a major and difficult problem. Currently only up to 20 percent of CRT glass is recycled back into the CRT glass manufacturing process, to produce new glass.

The used glass, called as cullet, enters the leaded-glass production process at the glass furnace operation stage, in the generic process model for leaded-glass. The cullet is mixed with the virgin leaded-glass in the furnace. But there might be some type of cleaning and sorting process before the cullet goes into the glass furnace.

For CRT glass, the maximum utilization of cullet should be encouraged and thus help in reengineering the CRT glass, which due to high lead content has disposal problem as the lead in it may leach underground.

5.8.3 Construction of Generic Process Model for Leaded-Glass

The discussion for developing the generic process model for leaded-glass is similar to that for steel, aluminum, copper, and lead. Figure 5.6 shows the generic process model for the production of leaded-glass from its ore.

The raw materials required, for the glass furnace operation, differ slightly with the type of glass that is manufactured. For example for the three glasses of CRT these materials vary in quantity and also, not all are used in each of them. So, detailed analysis for each CRT glass is indicated in the three separate inventory charts. Hence in the generic process model all the materials are shown, which are required for the production of all the three glasses, though most of them are common.

5.8.4 Detailed Inventory Chart for Leaded-Glass Production

The explanation and analysis of the inventory chart development is the same as for steel, aluminum, copper, and lead and hence not discussed again. The leaded-glass inventory chart is not complete due to lack of data on the emissions and the solid waste side. Considering the time frame of the research and the availability of good quality data, this is not really a drawback. Another important point worth mentioning for the lack of data,is the proprietary nature of the lead and the leaded-glass industry. Lead is a critical issue and hence it is very difficult to gather good quality data of these materials. Table A.5, Table A.6, and Table A.7 in Appendix A show the available detailed inventory charts for the three primary leaded-glass production process.

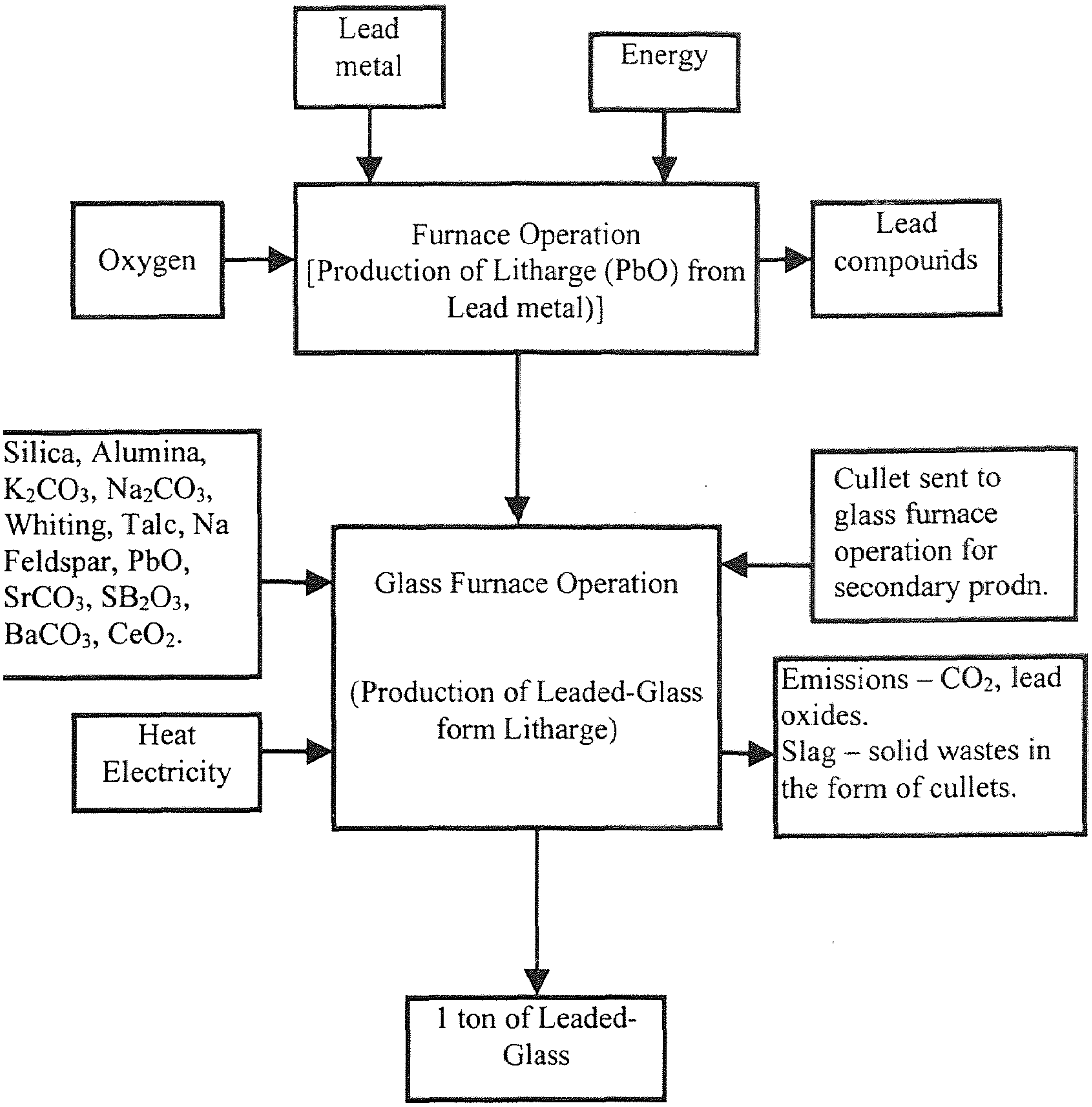


Figure 5.6 Production of Leaded-Glass

5.8.5 Environmental Impact Issues

The Gross Energy Requirement (GER) for the entire leaded-glass production is around 10,000 MJ/ton of leaded-glass produced. This is the average requirement, as the energy required for the glass furnace depends upon the percentage of lead in the glass. As the lead percentage decreases the energy increases. Hence, more energy is required for the panel compared to funnel and neck. The GER for leaded-glass is far less compared to that for aluminum, copper, and steel. But added to that GER of lead, then it rises up substantially. The secondary production of leaded-glass starts at the final stage in the generic process model, and hence it should be encouraged and increased to minimize the energy required.

The emissions from the leaded-glass production are mainly lead compounds, and some sulfur oxides. But they are very less and under control. During the glass furnace operation there are some CO_2 emissions. But again they are very low and hence do not contribute to the Global Warming Potential (GWP).

There are virtually no solid wastes generated during the leaded-glass production. There may be some slag in the form of refractaries but that is negligible. Some process waste in the form of cullets is generated, which is recycled back into the glass furnace operation process.

One important issue to mention about leaded-glass is its recycling. Currently only 20 percent of the leaded-glass form the CRT's is recycled. To tackle this problem, MERC has proposed this new term called as reengineering. MERC is striving to find new applications for this leaded-glass. The point is that if the leaded-glass can not be effectively used back into its manufacture then why not find new applications for that glass and hence eliminate the processing costs required before landfilling, as the glass contains which leaches when landfilled.

5.8.6 Notes and References

The data for the leaded-glass production process and the energy values for the glass furnace and the litharge production were obtained from a lead oxide manufacturer. Publicly available data was not found in any book, published journal, or internet searches and hence there are many data gaps in the inventory chart for leaded-glass and also for lead. The data received from the industry was only on the energy required for the glass furnace operation. This data is facility specific and hence can vary from manufacturer to manufacturer and not a average value.

5.9 Environmental Burden of a CRT

The final aim of a LCA is to calculate the environmental burdens over the complete lifecycle of any product. But, for this the quantification of various inputs, outputs, air emissions, and other solid and process wastes right from the raw material extraction stage till the final disposal of the product is necessary. In this research, the environmental burdens of a CRT from raw material extraction stage to the production stage are calculated.

The main raw materials used in a CRT are leaded-glass, steel, aluminum, and copper. For the purpose of calculating the environmental burdens of the CRT, the inventory analysis of these materials was conducted. Knowing the air emissions, solid wastes, and other process wastes generated during the production of these materials helps in allocating the environmental burden associated with the production of these materials.

The quantity of various air emissions, solid wastes, process wastes, and other effluents released during the production of these materials presented in their respective inventory chart are per ton of that material produced. So these quantities were appropriately calculated for the amount of the respective materials used in a CRT. As, the CRT was cut and disassembled in the MERC demanufacturing laboratory, the actual weights of all the components and hence the materials used in a CRT are known. And hence the air emissions, solid wastes, process wastes, and other effluents can be appropriately allocated. The energy consumed during the production of the materials is also allocated to the CRT. The energy consumed, air emissions, solid wastes, process wastes, and effluents during the production of CRT are adopted from the EIA's "CRT Benchmarking Survey."

Lead metal is not directly used in the CRT, but it is required for the production of the leaded-glass. So allocating the environmental burdens of production of lead is also essential. The percentage of lead in the CRT glasses is known and hence multiplying the weight of the CRT glass by lead percentage in it, the amount of lead required for the production of the CRT glass was obtained and then the energy consumed was allocated. Similarly the energy consumed during the production of leaded-glass was also allocated. The inventory charts for lead and leaded-glass is incomplete due to lack of data and hence whatever data was publicly available was included in the inventory chart.

All the available data for all the materials is tabulated in a table format and presented in Table 5.1, Table 5.2, and Table 5.3. Table 5.1 shows the total solid wastes generated from raw material extraction stage to the production stage of a CRT. Table 5.2 shows the total air emissions generated from the raw material extraction stage to the production stage of the CRT. And Table 5.3 shows the total energy consumed from the raw material extraction stage to the production stage of a CRT.

The sources for the data presented for the materials are the same as those cited in the inventory analysis chapter. But the data shown in these tables is in Kilograms as opposed to that in the inventory charts, which is in tons. Also, the carbon dioxide emissions indicated are not during the energy generation stage, but strictly are the emissions released to the environment during the production of the materials from different furnace processes. For steel, the data is not strictly for an integrated iron and steel plant but rather for a general steel smelter.

Thus, the environmental burdens over the lifecycle of a CRT from raw material extraction through its production are calculated and the final results are shown after the tables. The data for the production of the CRT is extracted from the Electronics Industries Association, CRT Benchmarking Survey. The values indicated in this survey are in pounds and hence were converted to kilograms. During this conversion the values were rounded off to the nearest integer. Also, the total recycled trash value was treated as process wastes and hence indicated in that row in Table 5.1. Water input, to the CRT production, indicated in the survey was not considered in this calculation. The calculations done are for a single CRT.

Table 5.1 Total Solid Wastes from Raw Material Extraction through Production of a CRT

Type of Solid Waste	CRT (Kg)	Steel (Kg)	Aluminum (Kg)	Copper (Kg)	Lead (Kg)	Leaded-glass (Kg)	Total (Kg)	% age of total solid waste
Water wastes	274.8						274.8	81
Hazardous waste	0.046				*		0.046	0.014
Slag		0.26	0.0085	59	*	*	59.27	18
Waste solvents	0.015						0.015	0.004
Process wastes	0.57	2.26		0.0003			2.83	0.84
Glass scrap	1.01					*	1.01	0.3
Waste oils	0.0054						0.0054	0.002
Waste water sludge	0.31						0.306	0.09
						Total Solid Wastes per CRT	338 (Kgs)	

Note: The numbers are rounded to the nearest integer and are in Kilograms.

Table 5.2 Total Air Emissions from Raw Material Extraction through Production of a CRT

Type of Air Emission	CRT (Kg)	Steel (Kg)	Alumin-um (Kg)	Copper (Kg)	Lead (Kg)	Leaded-glass (Kg)	Total	%age of total air emissi-ons
Oxygenated solvents	0.024						0.024	0.61
Halogenated solvents	0.00005						0.00005	0.001
Hydrocarbons	0.032						0.032	0.82
Carbon monoxide	0.001	0.0006	0.0035				0.0052	0.13
Nitrous oxides	0.006	0.014	0.0000002				0.02	0.51
Sulfur oxides		0.014		0.1	*		0.113	2.8
PM 10	0.001						0.001	0.03
HAP's	0.025						0.025	0.64
Form R	0.010						0.010	0.26
Particulates		0.0008	0.0001	0.004			0.005	0.13
Other gases and dust		1.93		0.12			2.05	52.3
Carbon dioxide		1.64	0.0029		*	*	1.643	41.8
Fluoride			0.0003				0.0003	0.008
Lead compounds					*	*		
						Total Air Emissi-ons	4.00 (Kgs)	

Note: All numbers are rounded to the nearest integer and are in Kilograms.

Table 5.3 Total Energy Consumed from Raw Material Extraction through Production of a CRT

Type of Energy consumed	CRT	Steel	Alu mi-num	Copp -er	Lead	Leaded-glass	Total	% age of total energy consumed
Electricity (KWh)	28	0.09	0.07	1.05	0.05		29.3	32
Fuel (MBTU)	0.14	0.001		0.006	0.01		0.16 (46.9 KWh)	51
Process Heat (MJ)			0.18			55.5	55.7 (15.47 KWh)	17
						Total Energy consumed	92 KWh	

Notes: All the numbers are rounded off to the nearest integer.

Sources of Data for all the three tables are:

- EIA's, "Bench-marking Study on CRT's"
- Battelle Columbus Laboratories, "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4 – Energy Data and Flowsheets, High Priority Commodities)," June, 1975
- Ayres R., Ayres, L., "Industrial Ecology: Towards Closing the Materials Cycle"
- EPA's, "Sector Note-books for the Non-ferrous Metals Industry"
- EPA's, "Sector Note-books for the Iron and Steel Industry"

From the Table 5.1 it was observed that, the major portion of the solid waste, nearly 81 %, is from the waste water generated during the CRT production process. Hence efforts should be implemented towards reducing the use of water or if not that then at least recycling that water back in to the production process. The total solid wastes generated for a CRT were 338 kgs. Table 5.2 shows that the major contribution of air emission is from other gases and dusts that are emitted during the production of the materials and the CRT. The total air emissions for the CRT were 4 kgs. Table 5.3 indicates that most energy consumed during the raw material extraction stage through the production stage is in the form of fuel. This should be reduced as usage of any kind of fuel for energy generation reduces the natural resources and also releases air emissions. The total energy consumed is 91.67 KWh ~ 92 KWh.

5.10 Discussion

Design for Environment (DFE) is an umbrella term for approaches and activities that incorporate environmental criteria into the design of new products and the redesign of existing products [26]. Design, which essentially is the idea from which a product is manufactured, dictates the selection of materials for the product. In DFE in addition to conventional design criteria's such as manufacturability, cost, aesthetics, etc., environmental criteria are explicitly added.

Materials use, their production, and consequently their end-of-life, will be greatly affected by DFE developments [26]. In traditional practices the material for a product is chosen on the basis of its strength, rigidity, manufacturability properties. So, the approach of selecting materials after the designing of products must be changed in the light of DFE. A more friendly approach to material selection must be adopted and the choice of materials should also depend on its end-of-life options and reengineering capability.

Also, in addition to intrinsic properties of materials like strength, stiffness, conductivity, the extrinsic properties for materials should also be considered [26]. The extrinsic properties that are addressed in this research are:

- Gross Energy Requirements – a measure of total primary energy consumption,
- Global Warming Potential – a indicator of emissions to the environment,
- Solid Wastes Burden – a measure of aggregate solid waste generation.

Materials can certainly not be compared on the basis of mass, density, thermal conductivity, etc., for evaluating their environmental criteria. So, this extrinsic approach to materials selection also leads a designer to compare materials and thus select them to reduce the total environmental impact of the product that is being designed, manufactured, and eventually going to be used. Also, because of the development of the generic process modeling structure, a first cut analysis can be immediately drawn for comparing the materials.

Another objective of performing the LCI of materials is to help provide the producer companies of these materials with an eco-profile of the materials they manufacture. This way the producers can evaluate the production process of the materials and incorporate changes to reduce the environmental impacts during the production process itself. The multi-lifecycle concept as applied to the materials can also be extended to include reengineering of materials to close the loop between primary and secondary production of materials to reduce overall environmental impacts.

Reengineering not only helps in solving the solid waste problem of materials from a disposed product, but also prevents up-stream burdens associated with primary production of materials, that are displaced by the reengineered materials. These prevented burdens not only include solid wastes, but also resource requirements, and air and water emissions.

Finally, it is expected that, with the help of this kind of data the product manufacturers should get a feedback of environmental improvements as they improve the environmental profiles of their products based on the selection criteria for different materials. This will eventually help in continuous environmental performance improvement of basic raw materials and also of products manufactured from these raw materials.

CHAPTER 6

DEMANUFACTURING OF A TYPICAL DISCARDED TELEVISION

6.1 Introduction

A few decades ago, the average family in the United States would have owned very few electrical items, and even fewer - if any - electronic ones. But, today the situation has changed dramatically. It is now not uncommon for that same average family to own a whole range of electronic items, including more than one television, computer, and other products such as washing machine, and telephone. There has been an equally rapid reliance upon electronic office equipment in business and industry. As a consequence there has been a marked increase in the number and volume of electronic products which, having reached the end of their useful life, are now being thrown away by households and companies.

Several estimates have been made by, different researchers on the number of these items being disposed every year. It is also estimated that two to three million tons per year of electronic scrap is generated annually, and this number will likely increase as the volume of electronic products increases [1]. The common solution to this problem is to either landfill or incinerate them. But from an economic point, this is not viable and from environmental point it is not benign. So, this chapter addresses a systems approach – *demanufacturing* - that supports the environmentally efficient and economically viable disposition of electronic systems and products, with specific focus on televisions.

As far as environmentally benign disposition is concerned, the consequences can be stated simply as reduction of toxic materials released into the waste stream, reduced solid waste, and resource conservation. From an economic standpoint, the objective is to ensure that maximum value is extracted from electronic products as it ends its useful life. Also, materials lacking any intrinsic value can be reengineered and can be managed in a cost efficient manner.

To address this problem, there are number of schemes proposed specifically – Western Europe, which strives to make the manufacturer take responsibility for goods at the end of their life - *product take back law* is one of them. Though measures to reduce wastes which constitute only a few percent of the total waste stream may seem misguided, electronic goods incorporate a number of characteristics which make them worthy of more attention, because of their increasing waste stream and inclusion of hazardous and toxic materials in them. They also contain significant amounts of valuable raw materials, which can be reengineered to reduce the virgin material requirement for the product's production. Also, their physical durability, even when no longer functioning, means that, once discarded, they will continue to occupy space in landfills for many years unless processed in some way or the other.

There are a number of different approaches to reduce the quantity and impact of wastes from electronic products. This research and thesis chapter focuses on one of them namely disassembly and reverse fishbone technique. A cost effective analysis is also conducted to aid in deciding the level of disassembly that should be performed, to make the operation economical. The sample used for the purpose of study and analysis is a typical 14" discarded television.

The demanufacturing options, developed in the Multi-lifecycle assessment approach, have already been discussed in the Methodology chapter and hence will not be addressed again. The remaining of the chapter concentrates on disassembly operation and analysis of a typical discarded television. The reverse fishbone technique is also used and its results are presented after the disassembly section.

6.2 Demanufacturing Approach

Demanufacturing is a end-of-life management option for economic and environmentally sound disposal of any product. Demanufacturing can be defined as the process of collection, disassembly, testing, cleaning and separating for reuse, or remanufacturing components, or reengineering valuable materials, of end-of-life products. In essence, it is source separation of plastics, metals, and glass from the waste stream.

The Land Ban Act, May 1994 – requires the generators of electronic waste to dispose of this waste in an environmentally benign manner. Only consumers and small quantity generators are exempted. All of the specific regulations set forth in this act can be found in Parts 260 through 279 of Title 40 of the Code of Federal Regulations (CFR) [38].

A typical TV set contains many reusable materials such as lead, silver, gold, cadmium, glass, plastic, and several metals. If the TV sets are disposed of in a landfill or in a incinerator the value of these materials is lost. Also, the environmental costs of disposing of this equipment can be high. It has been estimated that 70% of the toxins in landfills are accounted for by 1% of the landfills contents; principally consumer electronics. Over 2 billion pounds of plastic is used each year to manufacture consumer electronic products. However, less than 3% of that plastic is recycled [39]. The problem is therefore enormous and needs immediate attention.

If the TV sets are thrown in landfills or incinerators, they pose risks to the environment. But if demanufactured, then they pose opportunities for reuse, reengineer of valuable resources and also job creation. One more important aspect of the demanufacturing operation worth mentioning here is the creation of new jobs and potential for urban economic development. A demanufacturing industry is emerging for which an extensive transportation and collection infrastructure is needed, as the traditional distribution channels must be reversed to bring used products to a collection or demanufacturing facility [39].

Demanufacturing produces mainly two types of end-of -life opportunities for televisions. Firstly, the raw materials recovered from the wastes can be substituted for virgin raw material production and secondly, in terms of component recovery. The product often retains some value if remanufactured or refurbished, or made available for secondary markets. Even those televisions with no operating value may contain materials or sub-components that, if reclaimed and reengineered, have value for a variety of uses. Finally, components that contain nothing recoverable must be disposed of as waste in landfills or incinerated for energy recovery. This category is called as *fluff* in this thesis.

6.3 Disassembly Engineering

Disassembly Engineering is the systematic dismantling or taking apart of a assembled product, with the aim of reusing, remanufacturing, reengineering, landfilling or incinerating the components of the assembled product. In other words disassembly is a process which is applied for reusing abandoned goods and materials. The aim is to protect the environment and to regain the value added to products. Disassembly also helps is avoiding future high disposal costs imposed by legislation.

For some years, scrap metal dealers have recovered metal components from old equipment. They have used a relatively crude process to crush and shred the goods, sending the metal for remelting and landfilling the fluff. In order to recover the potentially valuable component parts of the wide range of different electrical / electronic products now in daily use, procedures for disassembling the scraped items must be identified. Disassembly is currently labor intensive and while there are studies into the automation of some procedures, it is not likely that the process could be fully automated unless single product disassembly centers are established.

Product designers are rarely concerned with the disassembly aspects of the product. Consequently, disassembly tends to be an expensive process and may not be a viable end of life option, unless disassembly engineering guidelines are applied at the product design stage. For example, in case of television parts, such as CRT glass, casings, front and back covers, can all be given a new life if televisions can be disassembled efficiently and economically.

Disassembly is a relatively new area with relatively little research conducted to date. Most of the research typically focuses on a narrow aspect of the disassembly process such as recycling. Also, models developed are restricted to a small class of products or material types. Over the last couple of years, methods for generating recovery plans or disassembly procedure for a given design have been developed. These methods typically attempt to balance the value of the reclaimed parts with the disassembly cost. One more emerging area is design for disassembly guidelines for the product designer.

The main aim of MLCE is to increasingly reclaim parts and subassemblies from used products to build new versions of the original product or alternative products, needs to be backed up by a strong disassembly structure. The development of disassembly tools such as the reverse fishbone diagram and technologies is important in efficiently and economically executing this reclamation process. The economic constraint in disassembly engineering is the value of the reclaimed, reengineered, or recovered part. What this essentially says is that for any industry to promote the multi-lifecycle concept, the disassembly cost should be lower than the value of the recovered, or reclaimed parts from the disassembly process. Thus, in order to make the disassembly process economically viable, a comprehensive disassembly strategy is required, which will essentially determine the disassembly level and disassembly sequences that provide conditions of generation of profit while the environmental concerns are addressed.

6.4 Disassembly Procedure and Analysis for the Television

The disassembly of any product needs a careful analysis in terms of the sequence dependency and independence of its components. A major factor in disassembly efficiency comes from the sequence independence of the retirement scenario. The reverse fishbone diagram explained in the next section graphically characterizes the difference between sequence dependent and independent disassembly specification.

Sequence independent disassembly is advantageous in that it allows overhead operation to be split among components, and permits many components to be removed or ignored without consideration of other components. Sequential disassembly, in contrast, requires that the system be disassembled according to a specified sequence of steps. This is usually undesirable. So, ideally, disassembly should have no sequence dependence. The horizontal branches of a disassembly diagram contain items that all depend on the overhead operations required to begin disassembly of the items on the respective branches. Finally, disassembly operations may require the design or purchase of special fixtures or tooling, or even redesigning of a part to reduce the cost and time of disassembly.

In this research and thesis a typical discarded television was disassembled. The remainder of this section describes the disassembly procedure and inventory list for the various components of the television.

6.4.1 Disassembly Procedure

The procedure for disassembling / dismantling a television is described in this section. This procedure is not necessarily a efficient process, but the reverse fishbone diagram study conducted for this television analyzes the economic aspects in terms of the number disassembly steps a demanufacturer should consider. For manual disassembly of a television, fixtures are not required and hence were not used in this research, except for the CRT disassembly, which is a technical consideration.

The steps for disassembling the television are as follows

- The first step is to separate out the antenna, which is screwed on the back cover by two screws. The antenna chord and its other connections also come out with the antenna. The tool required for this operation is just a medium philips head screwdriver.

- There are channel and volume control knobs on the front cover of the TV. These can be removed at this time by hand.
- After the antenna and its connections are taken out, the back cover can be disassembled from the television. The back cover which is screwed onto the front cover by nine screws is dismantled with the help of the medium head philips head screwdriver. The back cover has paper labels on the outside and the inside of it. This is particularly important to know, if the demanufacturer is to send the back cover for plastic recycling.

After the back cover is removed, the television needs to be oriented in the horizontal position with the front side of the television placed on the table. This is necessary to remove other components from inside of the television.

- The back cover has black plastic clips on it, which are removed with the help of pliers and also the channel assembly connections are unclipped, by hand.
- Next, the main CRT Printed Circuit Board (PCB), which is on the top of the copper-winding coil on the neck of the CRT, is removed with the help of a medium philips head screw driver and diagnals/cutters. There are several operations done during this time. The power and volume relay are unscrewed and other small components and wires are removed by hand.
- The power chord running to the CRT is removed by unclipping it with pliers.
- After this, the ground wire for the CRT is unclipped similar to the power chord with the help of pliers.
- Next, the vacuum cover on the CRT funnel outer surface is removed by hand.

- The main TV PCB is now ready to be disassembled. It is removed using the medium philips head screwdriver and diagnals. The main TV PCB can be further disassembled to remove the various metal components on it.
    - The various metal components were removed by desoldering the main TV PCB. Tools used were a solder gun and diagnals. The time required to remove each and every component on the PCB would have been enormous and so not all components were removed. Only those, which were large and more volume intensive were removed.
- The speaker and dials were taken apart at this stage. The speaker was screwed onto the front cover by four screws and hence necessitated the use of the medium philips head screwdriver.
- The horizontal and vertical controls next to the speaker were removed, again with the help of the medium philips head screwdriver. There were two screws.
- At this stage only the channel assembly and the CRT are left in the television in addition to the front cover. The channel assembly is disassembled from the TV with the help of the medium philips head screwdriver. There are three screws, which hold the assembly on to the front cover. The channel assembly consists of the VHF controller subassembly, the UHF controller subassembly, and the metal bracket which holds these two subassemblies together to form the channel assembly. So, the channel assembly can further be broken down as follows.
    - The VHF controller subassembly, and the UHF controller subassembly are screwed on to the metal bracket. After removing these screws the respective subassemblies are separated.

  - The UHF controller subassembly was further disassembled to separate various components of different materials in it. A medium philips head screwdriver and pliers were used to remove these components. The components separated were the cover, metal and copper parts, control knobs, and plastic parts. The objective was to recover plastic and metals separately from this subassembly. Whether this is economical or not is discussed in the reverse fishbone analysis section of this chapter.
- Then, the CRT is disassembled from the front cover. It is attached to the front cover by four screws and hence medium philips head screwdriver is required. The CRT itself is an assembly of different components made up of different materials; consequently further disassembling of the CRT by cutting it is necessary. As discussed in the CRT chapter, the CRT is composed of four glass components namely the panel, funnel, frit, and the neck. Because all these have different lead compositions in them, the effective and efficient separation of these is very important. Before the CRT is disassembled, several other components on the outside of the neck need to be removed.
  - The CRT disassembly process starts with the de-vacuuming of the CRT tube itself. This is done by making a hole at an opening provided on the tube for this purpose. The hole was made with the help of an awl and a hammer. The de-vacuuming operation took approximately 50 time units.
  - Next, the neck cap is removed. It was snap fitted on the open end of the neck. Hence pliers were used to remove it.

- Other small parts such as, the circlip and the brackets holding the copper winding coil, were removed by pliers.
- The copper winding coil, which is the largest component attached to the neck is disassembled. It was also snap fitted and hence required pliers and some hand force to remove it.
- After this, the implosion band, which is around the panel, is cut with the help of a hack saw.
- The tape, rubber spacers and corner spacers below the implosion band, were removed next. It is necessary to remove them, so that the panel glass is free from any other material. They were removed by hand.

After this the CRT was taken to the *Water Jet Machining laboratory* to separate the panel, funnel, and the neck.

- First, the neck was separated from the funnel at the joint where it is fused to the funnel, during the joining process. It took approximately 300 time units to do this operation. A special fixture was manufactured for this purpose.
- Then, the panel was cut near the frit line, keeping the frit with the panel. The panel had to be cut from all the four sides. The same fixture used for neck cutting was used for panel cutting too. It took approximately 1500 time units to cut the panel completely from the funnel. Other aspects about cutting such as cutting speed of the water jet, the diameter of the nozzle, the feed rate, etc. also affect the time for cutting the CRT.
- Now that the panel is separate from the funnel, other components inside the panel can be removed. The aluminum foil spacer, which is around the inside

edge of the panel is removed by pliers. Then, the electron shield and the shadow mask are disassembled, by using pliers. Care has to be taken during the disassembly of these components, as lead and phosphor coatings are released during the disassembly operation. So, a mask is recommended for this kind of disassembly operation.

- Next, the electron gun assembly is removed from the neck portion of the CRT. The only way to remove it is to pull the electrodes by pliers.

This completes the disassembly of the CRT. The total time required for the complete disassembly of the CRT was 2325 time units. The time to fixture the CRT for water jet cutting and other handling time were not considered.

- The last component that remains after taking out the CRT and the channel assemblies is the front cover. The front cover has a label on its inside surface. There are also channel and name labels, which are laminated on the front cover. Finally, there are some plastic nuts on the top and inside of the front cover.

This completes the entire television disassembly operation. The analysis of the disassembly operation is discussed in the following section. Figure 6.1 shows the disassembly diagram for the main TV. The disassembly diagrams for CRT and Channel assembly are also included in figure 6.1. The letters ‘A’ and ‘B’ in the main TV disassembly diagram indicate these assemblies. Below the main TV disassembly diagram, the tools used for disassembly are also indicated.

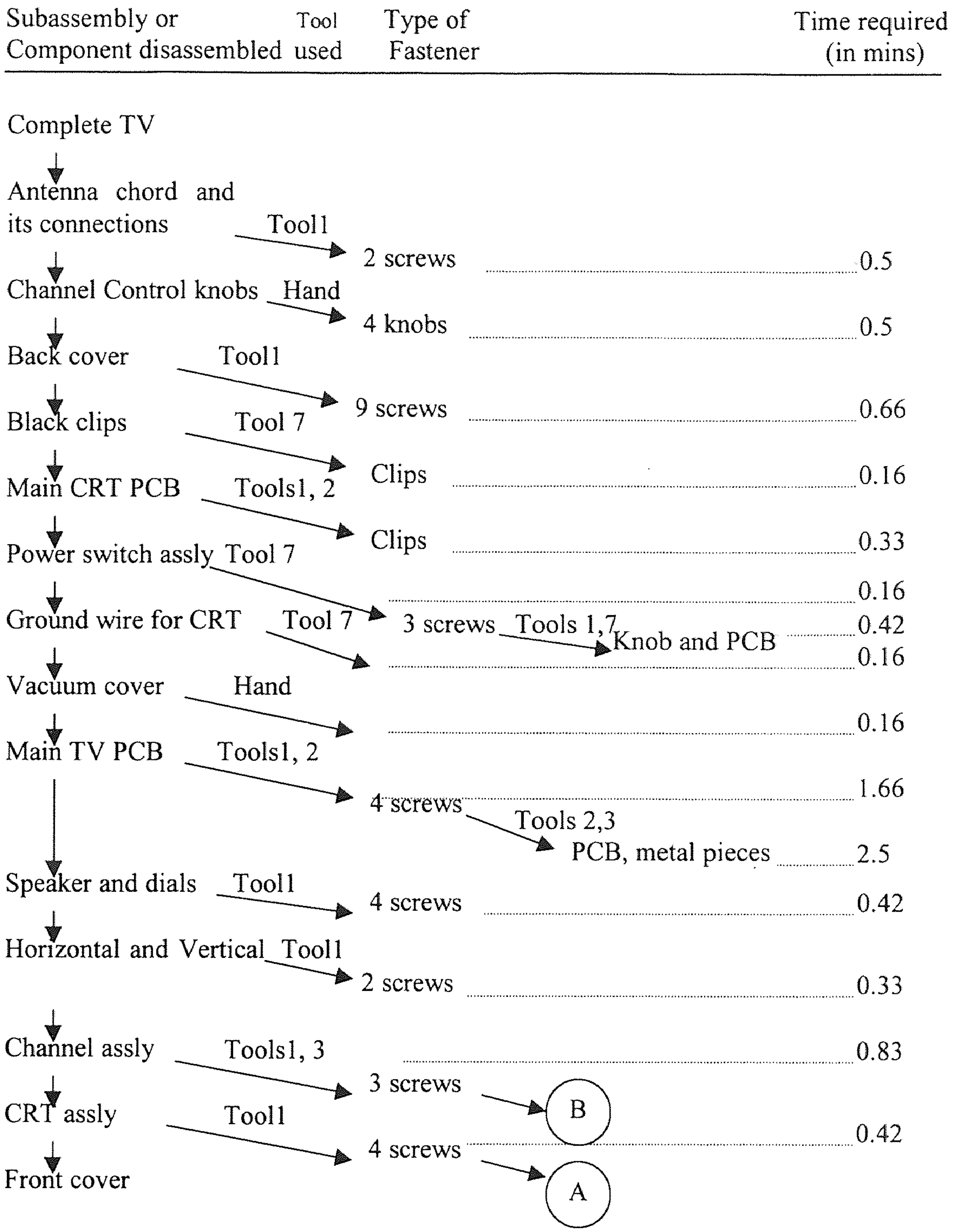


Figure 6.1 Television Disassembly Diagram

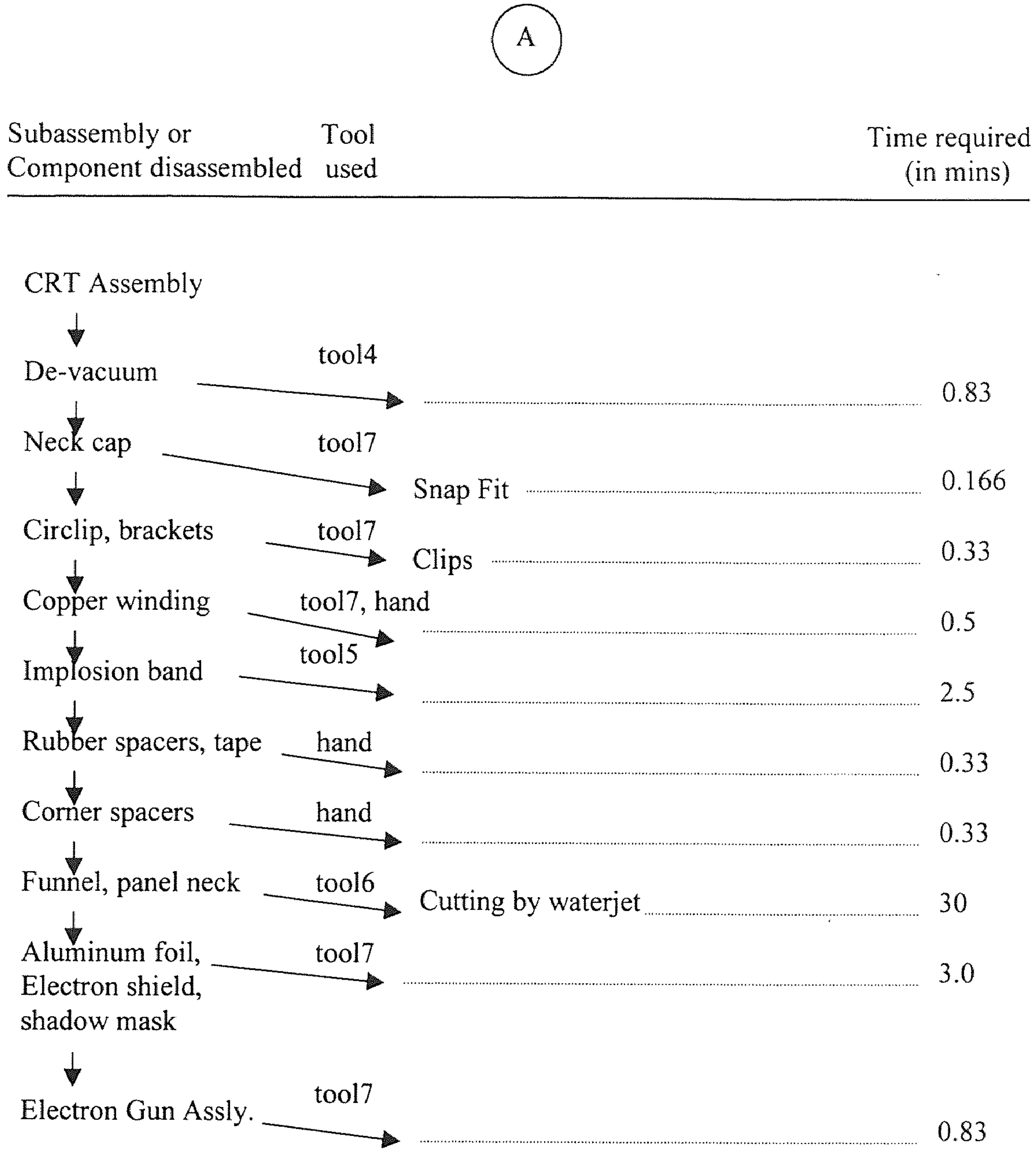
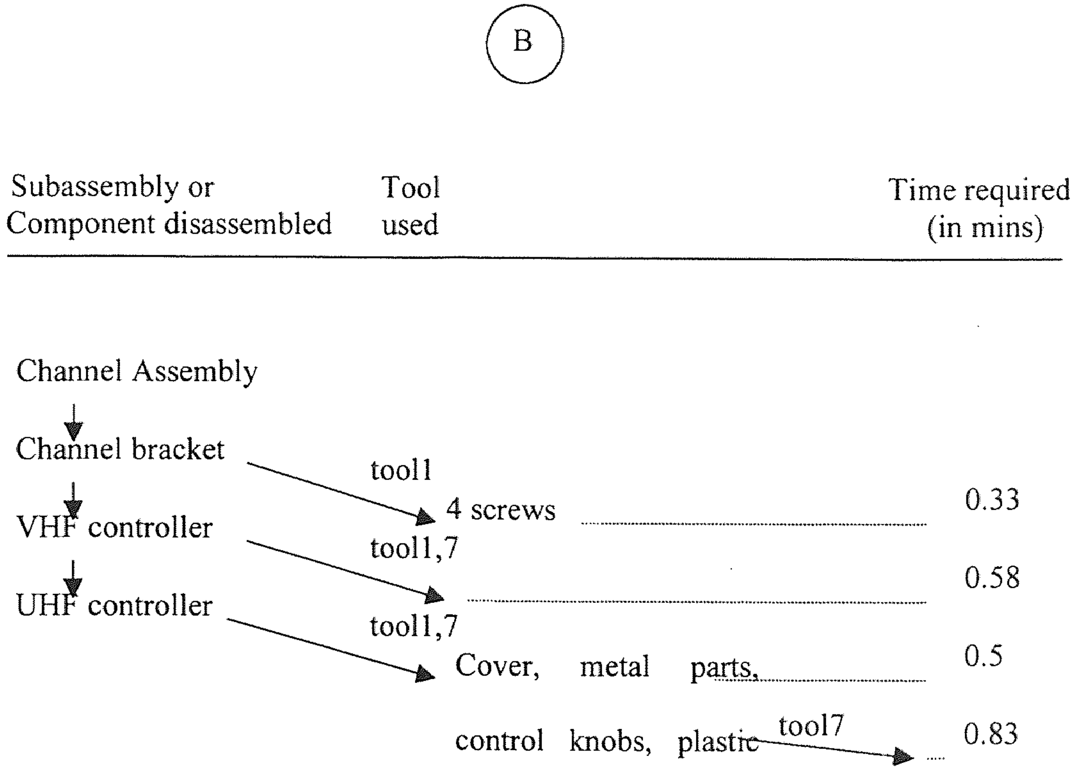


Figure 6.1(Cont.) Television Disassembly Diagram



Tools:

1. Medium Philip's head screwdriver
2. Diagnals
3. Solder Gun
4. Awl
5. Hack saw
6. Waterjet
7. Pliers

Figure 6.1(Cont.) Television Disassembly Diagram

6.4.2 Disassembly Analysis

The total time required for the complete disassembly of the TV was 3020 time units. The total time was distributed among the three main disassembly operations: basic disassembly of the TV, disassembly of the CRT assembly, and disassembly operation of the channel assembly. The CRT assembly was the most time consuming operation mainly due to the water jet cutting of the CRT. The disassembly time distributed among the three assemblies is shown in Table 6.1 as follows.

Table 6.1 TV Disassembly Times

Disassembly operation	**Time required (in minutes)**
Main TV	9.25
Channel Assembly	2.25
CRT Assembly	38.83
Total	50.33

The disassembly time (9.25 min.) for the main TV is the time required for removing all the components including the CRT assembly and the channel assembly from the television. The actual disassembly time depends entirely upon the level of disassembly decided by the demanufacturer. If the demanufacturer decides not to disassemble the CRT and the channel assemblies, then the total time required for the entire operation would be just 9.25 minutes. So, depending upon the disassembly plan and level of disassembly the demanufacturer, the time may reduce or increase. The economics of the disassembly time is related to the number of disassembly steps, as well as the skill and experience of the disassembler. This was the first television disassembled in the MERC demanufacturing laboratory and was done with no prior experience. Consequently a demanufacturer with skilled and experienced labor trained for only this kind of activity, can significantly reduce the time required.

There are other factors that play important roles in determining the most effective disassembly procedure and operation. One important aspect in the demanufacturing industry is the technology used for the disassembly operation, and especially for CRT disassembly. Different demanufacturers use varied technologies for cutting the CRT. For example, Electronics Product Association Inc. (EPA INC.) facility in New York cuts the CRT by wrapping a wire around the panel near the frit line and then heating the wire. After that the panel is hit by a hammer and separates from the funnel. In this technique EPA Inc. separates the panel such that the frit is with the funnel rather than with the panel.

Another demanufacturer in New Jersey, with a press, in which the CRT's are crushed uses destructive disassembly. The advantage in this kind of disassembly technology is that the time required to cut the CRT is low; however the CRT glass is crushed into larger pieces which are mixed and not separated. Glass is then sent to a secondary lead smelter, to recover the lead. Because the glass is mixed, recycling back into CRT's is not viable.

There are actually several factors, which influence the CRT demanufacturing:

- The end objective of the disassembly process in terms of the fate category of the components. For example, the above mentioned demanufacturer creates commingled glass after the destructive disassembly while other demanufacturers may want to keep the three glasses separate to send them back into the leaded glass production. Commingled glass has a low value then separated glass; however, processing costs are less.
- The type of technology used to cut the CRT also affects the economics of the operation. For example, the water jet technology used in this research generates almost negligible solid waste when the CRT is cut. Also, the water emissions generated during the cutting are absorbed and hence there are no air emissions.
- Collection and transportation of CRT's is also crucial for the demanufacturer. There should be a good collection infrastructure in coordination with the municipalities, public, and private companies.
- The type, size, age, and diversity of televisions also has a considerable impact on the disassembly process. As different manufacturers produce different models of TV's with varying internal structure, automating the disassembly process is difficult. This problem is more severe in the case of CRT's, as every CRT manufacturer has somewhat different compositions and percentages of lead in the three different CRT glasses. The age of the TV certainly has an impact on the demanufacturing process, because the CRT glass technology has been changing, and currently the panel has almost zero percent lead. Whereas discarded TV's which are 10-20 years old will have different lead compositions in their panel, funnel, and neck and hence make it difficult to reengineer into current CRT glass manufacturing.

- One important aspect in design for disassembly is the type of fasteners, used for connecting the components. It was observed in this television that, all the screws were of same size and hence only one type of screw driver (medium philips head screw driver) was necessary. This is a very important criteria, because if different types and sizes of fasteners are used, then the disassembly time and effort can increase due to changing of tools. This in turn also leads to increase in the inventory of tools necessary for the demanufacturing operation. A solder gun is necessary if the metal components on the PCB are to be recovered. But as discussed earlier it depends upon the demanufacturer whether to remove these components or send the PCB directly to a lead smelter. The tool used for cutting the CRT was water jet machine. Other tools used were, an awl, diagnals, hacksaw, and pliers. One interesting point to note is the use of hands in disassembly. The channel control knobs, and vacuum cover in the television and rubber spacers, corner spacers, and copper winding were removed by hand without tools.
- There were approximately 35 fasteners used in this television. This number should still be reduced, by incorporating snap fits wherever possible. Of course the larger assemblies, such as the CRT and channel assembly cannot be snap fitted, but some components such as the antenna, main TV PCB, speaker and dials, and the horizontal and vertical control can be snap fitted. This helps in reducing the time and effort involved in the disassembly operation.
- The disassembly diagram also indicates the disassembly times for all the individual disassembly operations performed. More detailed discussion about the time and level of disassembly operation is explained in the cost-effectiveness section of this chapter.

- There are some suggestions that should be incorporated in the television, to improve the assembly and also the disassembly process. All the control circuits including the control knobs should be assembled on a single board. This will help in reducing the disassembly time as all can be removed together. Moreover all the control knobs are made of the same material. So, if the board too is made of the same material, they all can be removed and thrown in the same bin.
- All the dials can be eliminated and replaced with push buttons. In present day televisions there are push buttons, so the above statement was just an analysis of the television that was disassembled.
- All the current electrical circuitry should be replaced by electronic circuitry, which is definitely incorporated in present televisions due to advances in PCB technology. So, this observation too was with respect to this particular disassembled TV.
- During the disassembly operation, bins should be located around the work table, in order that the worker does not waste time in thinking and arranging the sub-assemblies, and components.
- Lastly, power tools such as the power screw drivers should be used to expedite the disassembly operation.
- One important point to be noted during this entire study is the inexperience of the researcher in disassembling the television. And also, this was the first time a television was disassembled without any prior knowledge of the disassembly process and also without any end-fate objectives for the recovery of materials.

6.4.3 Inventory Analysis for the Television

A inventory list of the disassembled television was generated. The list consists of following items:

- The first item is the 'part/sub-assembly'. This item identifies the names of the various sub-assemblies and components in the television. This identification helps the disassembly workers to understand the disassembly operation.
- The second item is the 'material'. This column characterizes the sub-assemblies and components identified in the earlier step. The type of material of which the sub-assembly or the component is manufactured is identified. This identification is particularly important in deciding the fate categories of these sub-assemblies and components.
- The third column consists of the 'weight' of these sub-assemblies and components. This is also important as it helps in the cost effectiveness analysis, which is discussed later. By knowing the weights, the component, which has the most weight, can be identified and action can be taken to reduce the weight of components that make the entire TV heavy. One thing to note here is that the weights indicated are the total weights and not of just one quantity. So, even though if some components are indicated that they are say four in quantity, then the weight indicated is for all four of them and not for the individual piece.
- The last and the fourth item is of 'quantity'. In this column the quantity of each component is indicated. With few exceptions everything is just a single quantity.

Table 6.2 shows the materials inventory list for the typical discarded television. The table also shows the CRT components and their materials in detail.

Table 6.2 Typical Discarded Television Inventory List

Part / Sub – Assembly	Material	Weight (gm)	Quantity
Front Cover	Polystyrene	1199.85	1
Back Cover	Polystyrene	1029.66	1
Black clips	Mixed Plastic	5.000	2
Antenna	Steel	95.12	1
Antenna Connections	Steel	7.520	4
Speaker	Steel (Cad. Coat)	57.03	1
Channel control knobs	ABS	3.460	4
Channel Assembly		702.75	1
Channel bracket	Steel	116.52	1
UHF sub-assembly		236.77	1
Channel indicator	Polystyrene	17.50	1
Turn knobs	ABS	16.10	2
Fine adjustment knobs	ABS	14.45	2
Metal parts	Steel	125.58	3-4
Copper coils	Copper	4.420	
Plastic components	Poly-Acetal	22.9.0	3-4
VHF sub-assembly	Steel	349.46	1
Dials	Mixed Plastic	6.32	2
Main TV PCB	Thermoset	252.43	1
Metal pieces	Steel	124.13	4-5
Power Switch Assly.		36.60	1
Plastic knob	Mixed Plastic	17.80	1
PCB	Thermoset	18.80	1
Horiz. & Vert. Control		110.0	1
Plastic parts	Mixed Plastic	25.00	1
Metal parts	Steel	85.00	2
Vacuum cover	Rubber	69.20	1
Power cord	Copper	108.7	1
Other wires	Copper	25.00	3-4
Screws	Steel	65.00	35
CRT		5795.91	1
Panel and Frit	Leaded Glass	3401.36	1
Funnel	Leaded Glass	1744.43	1
Neck	Leaded Glass	39.53	1
Screen	Steel	394.35	1

Table 6.2 (Cont.) Typical Discarded Television Inventory List

Shadow-mask	Steel	60.56	1
Aluminum foil	Aluminum	4.460	1
Electron gun assembly	Steel, Nickel	13.64	1
Implosion band	Steel	115.32	1
Main CRT PCB	Thermoset	41.01	1
Ground wire for CRT	Copper	41.80	1
Copper winding	Copper	318.95	1
Neck cap	Mixed Plastic	5.030	1
Circlip, Bracket and other Metal pieces	Steel	63.09	5
Rubber Spacers	Rubber	6.100	2

There are some components whose material is not identified, but these components are in the mixed plastic's category. The metals identified were mainly steel, copper, and aluminum. The panel, funnel, neck and the frit are made of leaded glass. The percentage of lead in these glasses varies, and is indicated in the inventory list. The lead percentage was tested by a commercial laboratory - International Testing Laboratory, which is fully certified to conduct the test. But before sending the glass samples to this laboratory the water jet machine was used to cut glass samples from the panel, and funnel. The entire neck was sent as it is. The Center for Ceramic Research at Rutgers crushed and grind the three samples into fine powder form fit for the lead content testing. The results for the lead content in the three glasses were not available till now and hence not included in this thesis.

6.5 Reverse Fishbone Diagram Technique and Analysis

The Reverse Fishbone Diagram (RFBD), proposed by Prof. Kosuke Ishii and Prof. Burton Lee, is essentially a disassembly tool, which graphically describes the disassembly process. It is a communication tool to promote environmentally conscious product design [39]. It is a emerging analytical tool used during the design and evaluation of product retirement process for minimal environmental impact.

The Design for Assembly (DFA) concept is being used by many manufacturers, but Design for Disassembly concept is relatively new. There are many DFX tools, such as Design for Recyclability (DFR), Design for Product End of Life Management (DPELM), Design for Product Retirement (DFPR), and so on, currently being researched and also some of them are being used. In this research and thesis a reverse fishbone diagram for a television is generated.

Reverse fishbone diagram is a relatively new disassembly analysis tool in close concert with design for manufacturability tools. The concept of the reverse fishbone diagram can be explained as follows [39]:

- It is most effective when implemented at the layout design stage, so that designers can identify disassembly complications and ensure that product retirement concerns are addressed up front.
- Reverse fishbone diagram is a method of describing and evaluating disassembly sequences, which promotes a structured approach to advance planning of the disassembly and the sorting process.

- The diagram is an effective tool for a designer to assess the disassembly process, identify disassembly difficulties, analyze cost intensive disassembly tasks and steps that lead to defects, and synthesize towards solutions.
- The RFBD schematically describes the disassembly steps for the product and also specifies the retirement intent or fate category for each clump.

In short the concept is to graphically represent the disassembly procedure taking into consideration the sequence independency of the disassembly operations and simultaneously identifying the fate category of each component.

6.5.1 Data Required for Construction of Reverse Fishbone Diagram

The construction of the reverse fishbone diagram needs some prior information and analysis of the product and, if possible, the product family itself, in terms of its serviceability. From the service perspective, the reverse fishbone diagram provides a good starting point as it helps in targeting the items for later use. It is good to know the subassemblies of the product that require critical analysis in terms of disassembly and the associated costs, before starting the reverse fishbone diagram.

A major point before starting the RFBD is to identify and then prioritize the subassemblies, and components that are to be targeted for reuse, and reengineering. This helps in understanding the post-disassembly fate categories and also an optimal disassembly procedure can be formalized. A fate category, of a component is its final destination after the disassembly, and sorting operations. Table 6.3 shows the different fate categories for sub-assemblies and components. The table shows very generic fate categories, and detail categorization can be done depending upon the specific product and the manufacturer.

Table 6.3 Generic Fate Categories for Sub-assemblies and Components in Typical Electronic Products

Fate Category	Description of the fate category
Reuse	Retain for further use or testing services in existing products.
Remanufacture	Retain for further use in the product manufacturing process, by upgrading the sub-assemblies and the components.
Grade 'A' Bin A1 – Metals A2 – Plastics A3 – Glass	Reengineering – Raw materials are reprocessed to enter back in to the product production process, thus reducing the virgin raw material requirement.
Grade 'B' Bin	Additional post-processing required such as removal of high value chips, from PCB's and then sending the PCB's to smelter.
Grade 'C' Bin	Commingled or Dirty (contaminated) category – The subassemblies or components that are not pure in any one material and hence are contaminated are included in this bin category.

Table 6.3 (Cont.) Generic Fate Categories for Sub-assemblies and Components in Typical Electronic Products

Grade 'D' Bin	Fluff category – All remaining components are ground and either sent to incinerator to recover energy or landfilled.

6.5.2 Construction of the Reverse Fishbone Diagram

The steps required for constructing a reverse fishbone diagram are as follows,

- A detail study of the disassembly diagram and procedure itself is necessary before getting started on the RFBD.
- Identify subassembly and component disassembly operations that are not, sequence dependent, but can be carried out simultaneously. Sequence independent steps are shown on the same horizontal level; while sequence dependent steps flow down the diagram from top to bottom.
- Identify and assign fate categories of sub-assemblies and components.
- Start construction of the reverse fishbone diagram in a "top down" fashion, as the designer walks through, or physically disassembles, the product.
- Include symbols such as component fate category, fixturing requirements, removal directions, time needed for each disassembly operation, and connection separation method (break, unscrew, unclip, pop).
- Indicate the tool used for disassembling and removal difficulty, as it facilitates the rapid visual evaluation of disassembly difficulty.

- The RFBD ends when all the sub-assemblies, and components with an assigned fate category are removed, such that further disassembly is not possible, or required.

Apart from these steps there are other things that a demanufacturer must take care of. For example, those subassemblies or components that require excessive time for disassembling, due to the number of fasteners or rivets, should be removed last, so that time is not wasted in recovering individual materials. This again points to the problem of level of disassembly and the end objective of the disassembly process. Disassembly is not necessarily the reverse of assembly. Hence assembly fishbone diagram should not be reversed to generate a disassembly and reverse fishbone diagram. Lastly, designer should identify where optimal disassembly requires changes in fixturing, orientation, direction of action, and conductivity from the assembly procedure [39].

The information on type of tools used, the time required for disassembly, fixturing requirements, and the connection separation method are indicated on the disassembly diagram. The RFBD generated here indicates the retirement or the fate category of the sub-assemblies and components. RFBD also indicates the sequence independent and dependent disassembly operations. Another important aspect it points towards is the level of disassembly that is required for economic operation of the demanufacturing facility.

Three reverse fishbone diagrams were generated, for the television disassembled, using the above procedure and guidelines. One of the diagram is very detailed, which indicates all the sub-assemblies and components in them that were disassembled down to basic materials. The second and the third RFBD's, which have different end-fate objectives are generated for cost effectiveness analysis. Figure 6.2 shows the first reverse fishbone diagram, which is generated for recovery of basic materials. Figure 6.3 shows the second reverse fishbone diagram generated for recovery of subassemblies and components. Figure 6.4 shows the third reverse fishbone diagram generated for recovery of only the CRT from the entire television.

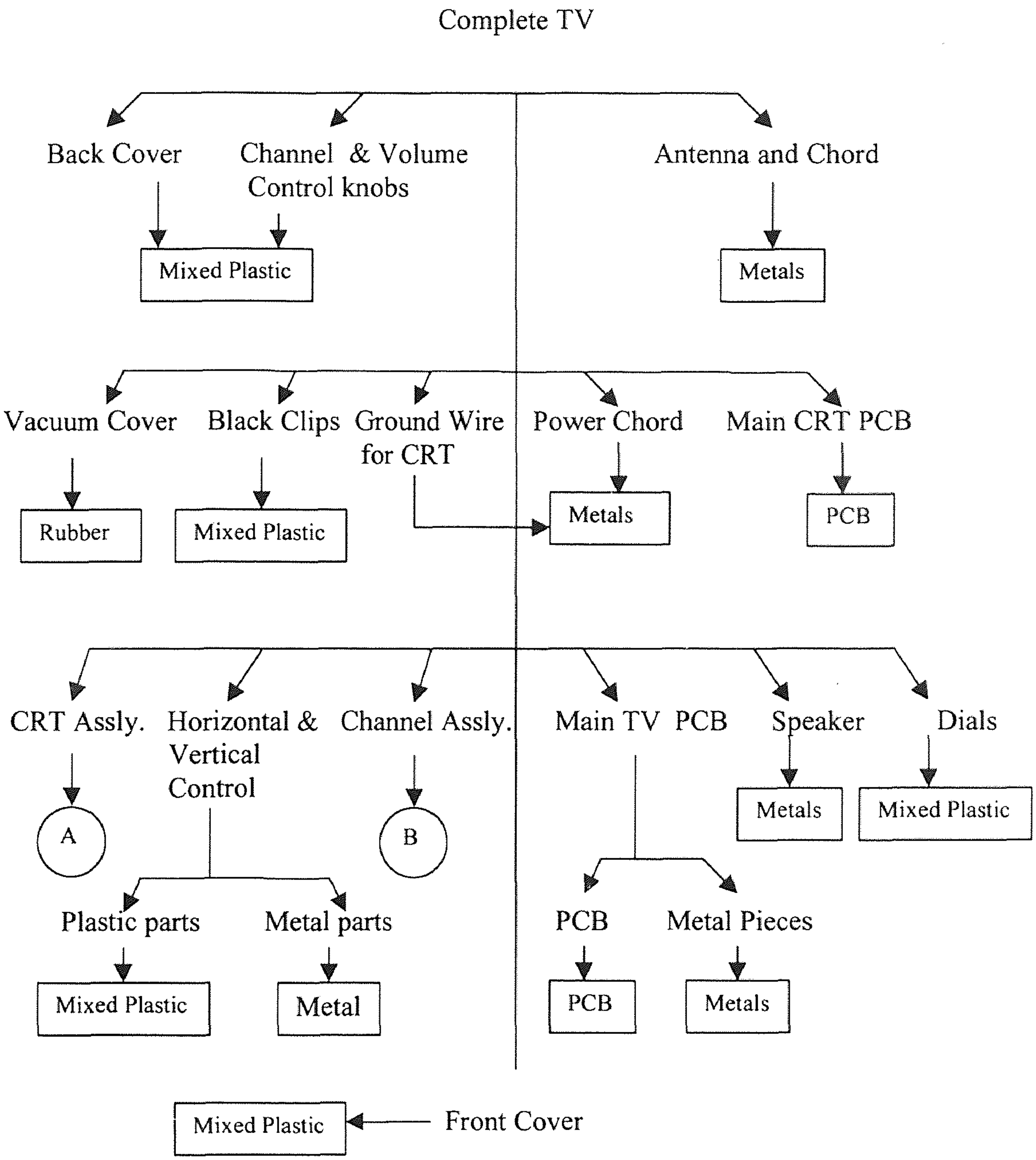


Figure 6.2 Reverse Fishbone Diagram 1

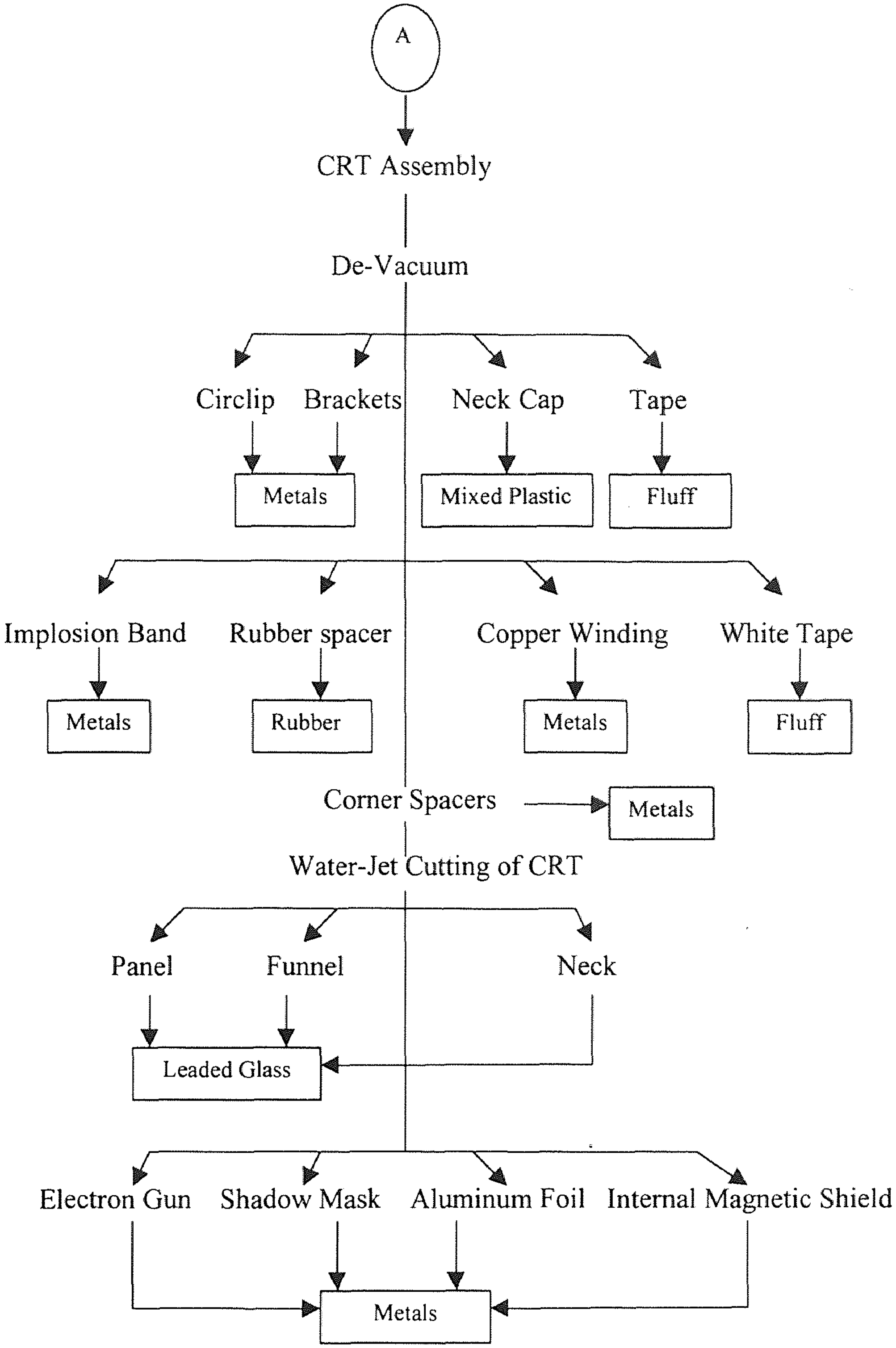


Figure 6.2 (Cont.) Reverse Fishbone Diagram 1

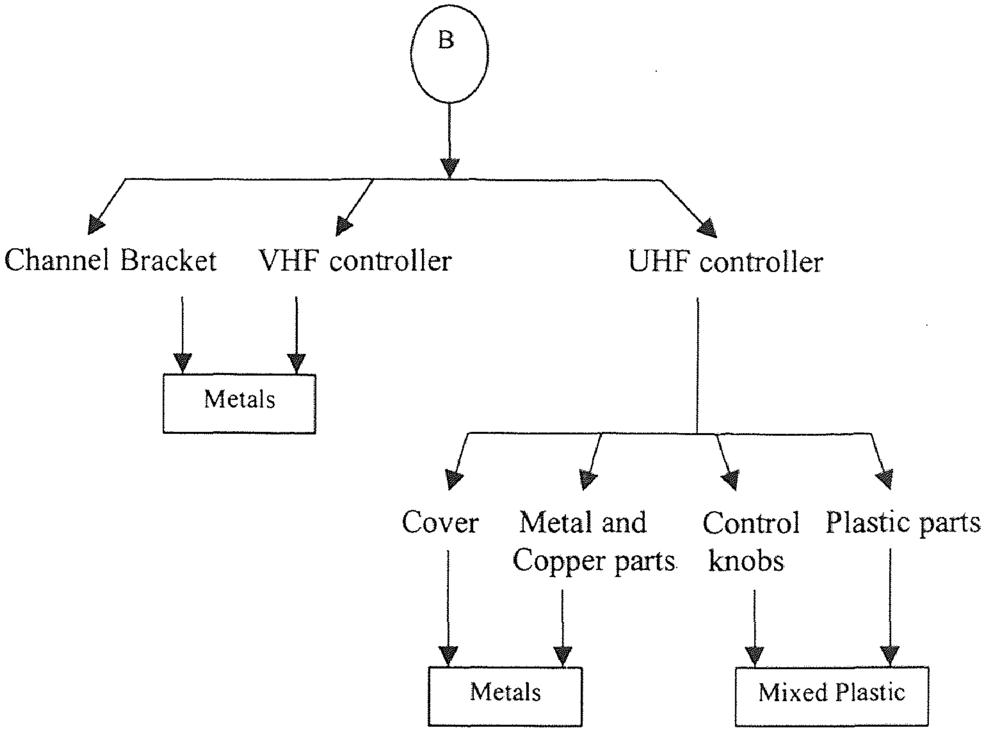


Figure 6.2 (Cont.) Reverse Fishbone Diagram 1

The first reverse fishbone diagram was generated to recover all the materials in their pure form and hence it shows the disassembly of the television till the last level.

The second reverse fishbone diagram in contrast is generated to recover mainly the CRT and the subassemblies. The subassemblies are recovered as commingled materials and sent to a metal smelter.

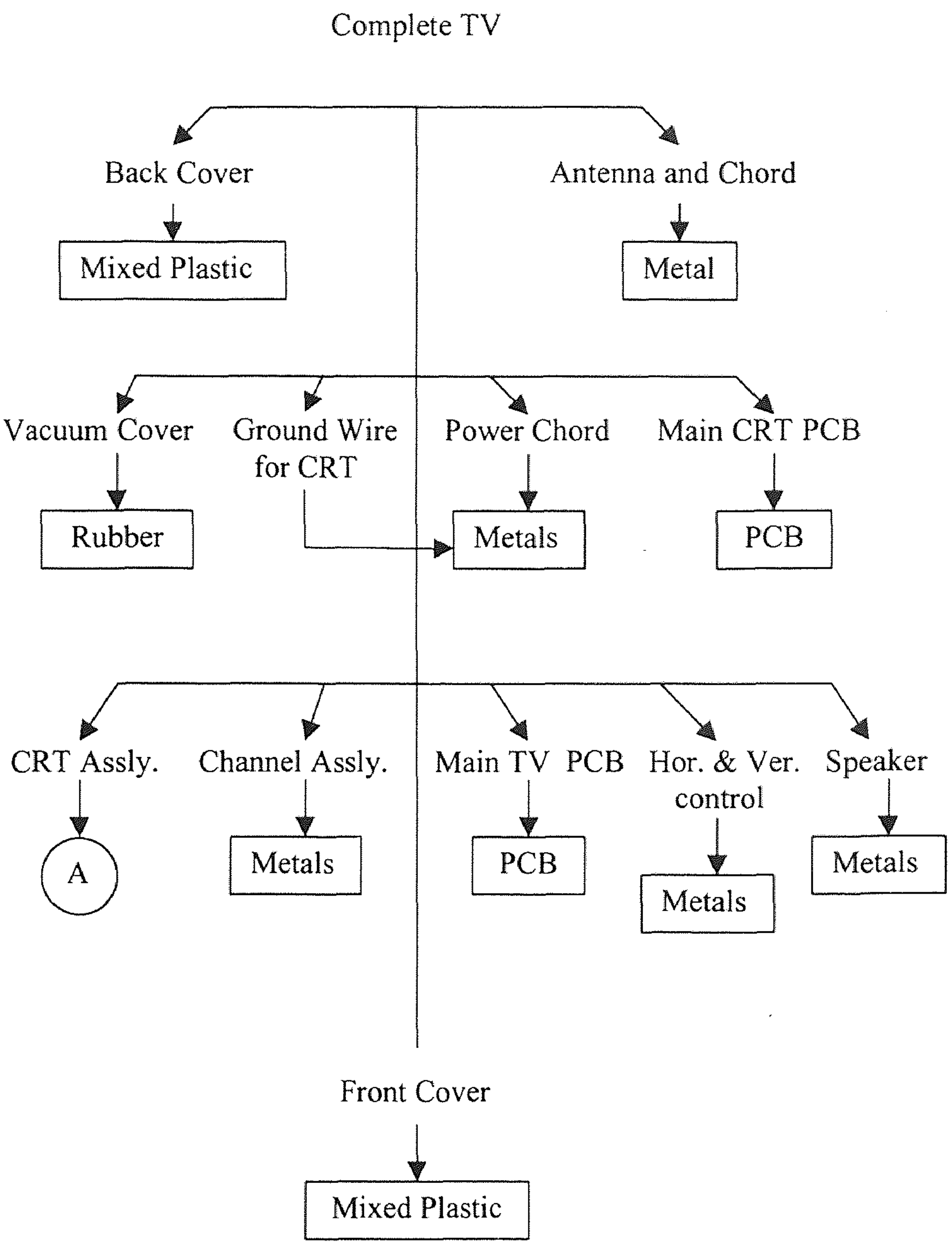


Figure 6.3 Reverse Fishbone Diagram 2

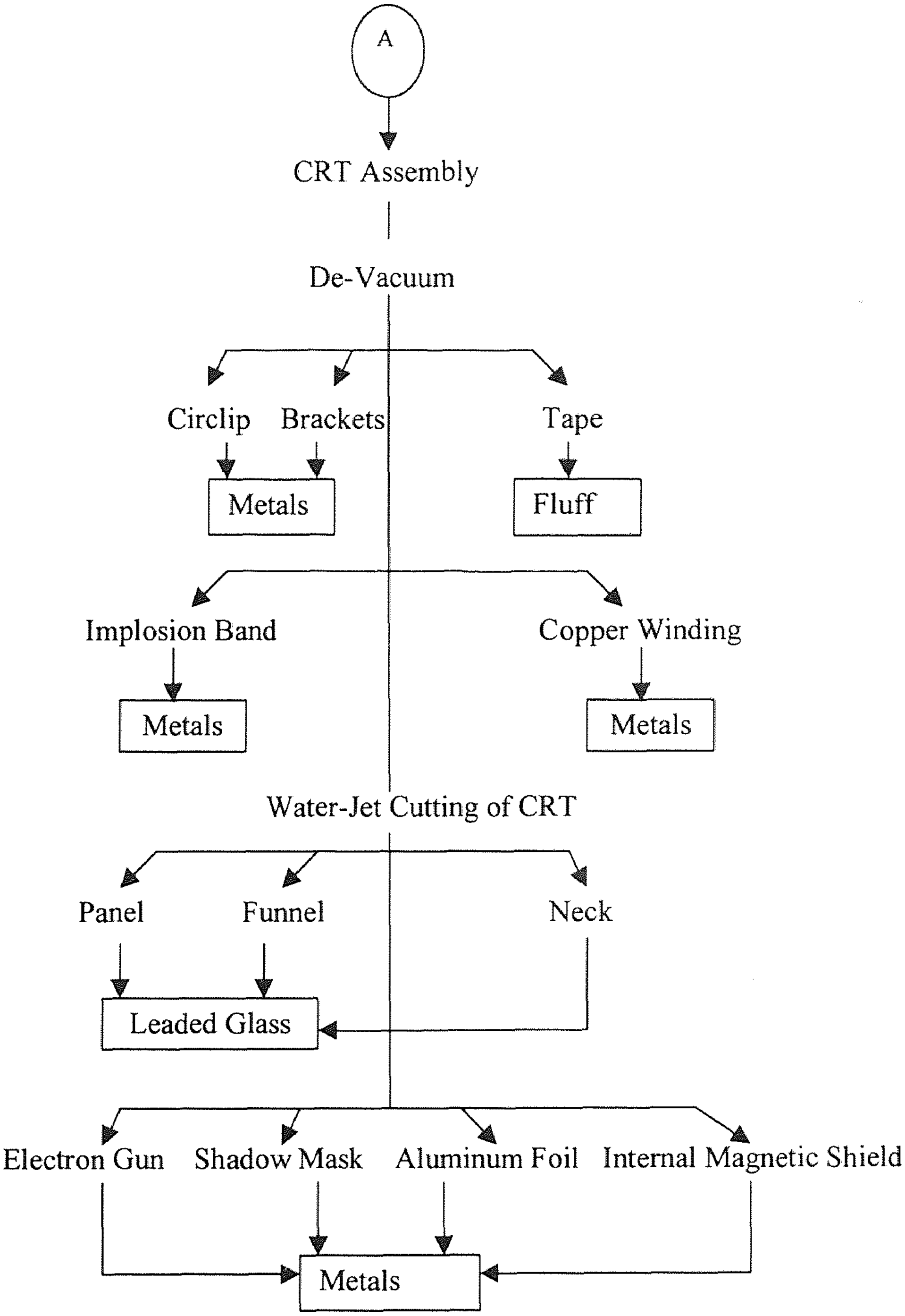


Figure 6.3 (Cont.) Reverse Fishbone Diagram 2

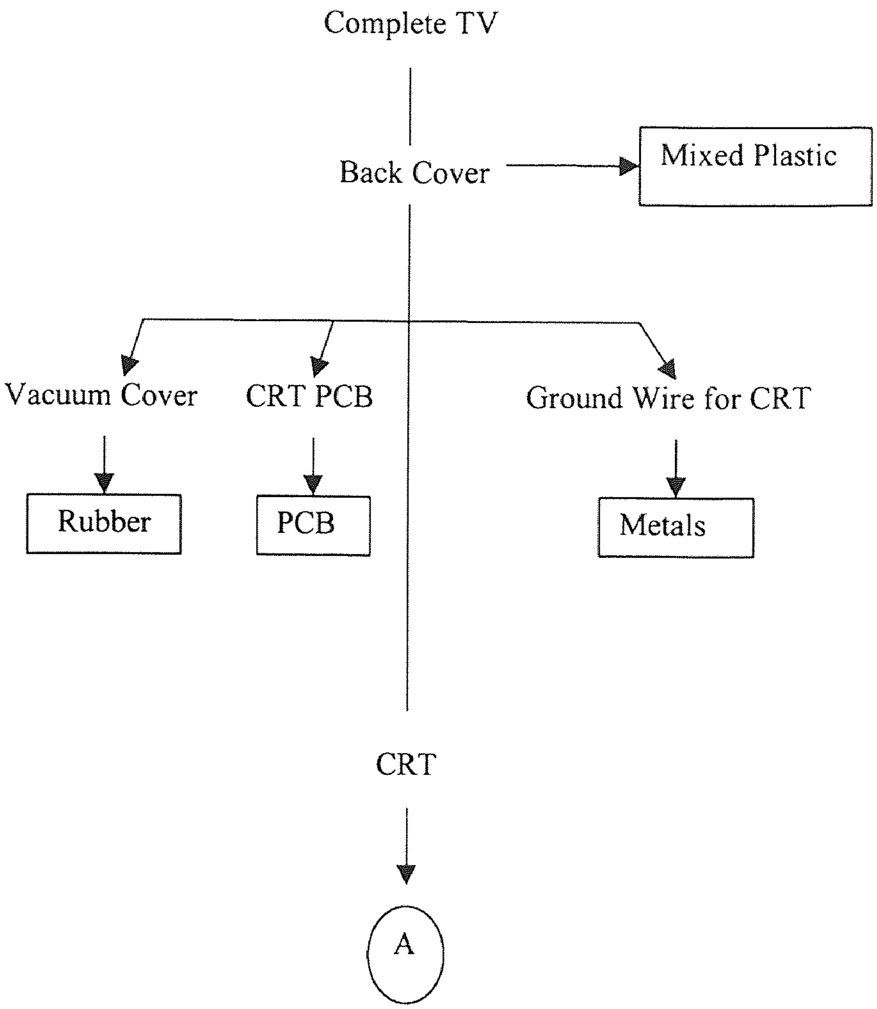


Figure 6.4 Reverse Fishbone Diagram 3

The third reverse fishbone diagram is generated to recover only the CRT. It can be observed from the diagram that only the back cover, and components, such as the vacuum cover, the CRT PCB, and the ground wire for the CRT, need to be removed, in order to recover the CRT.

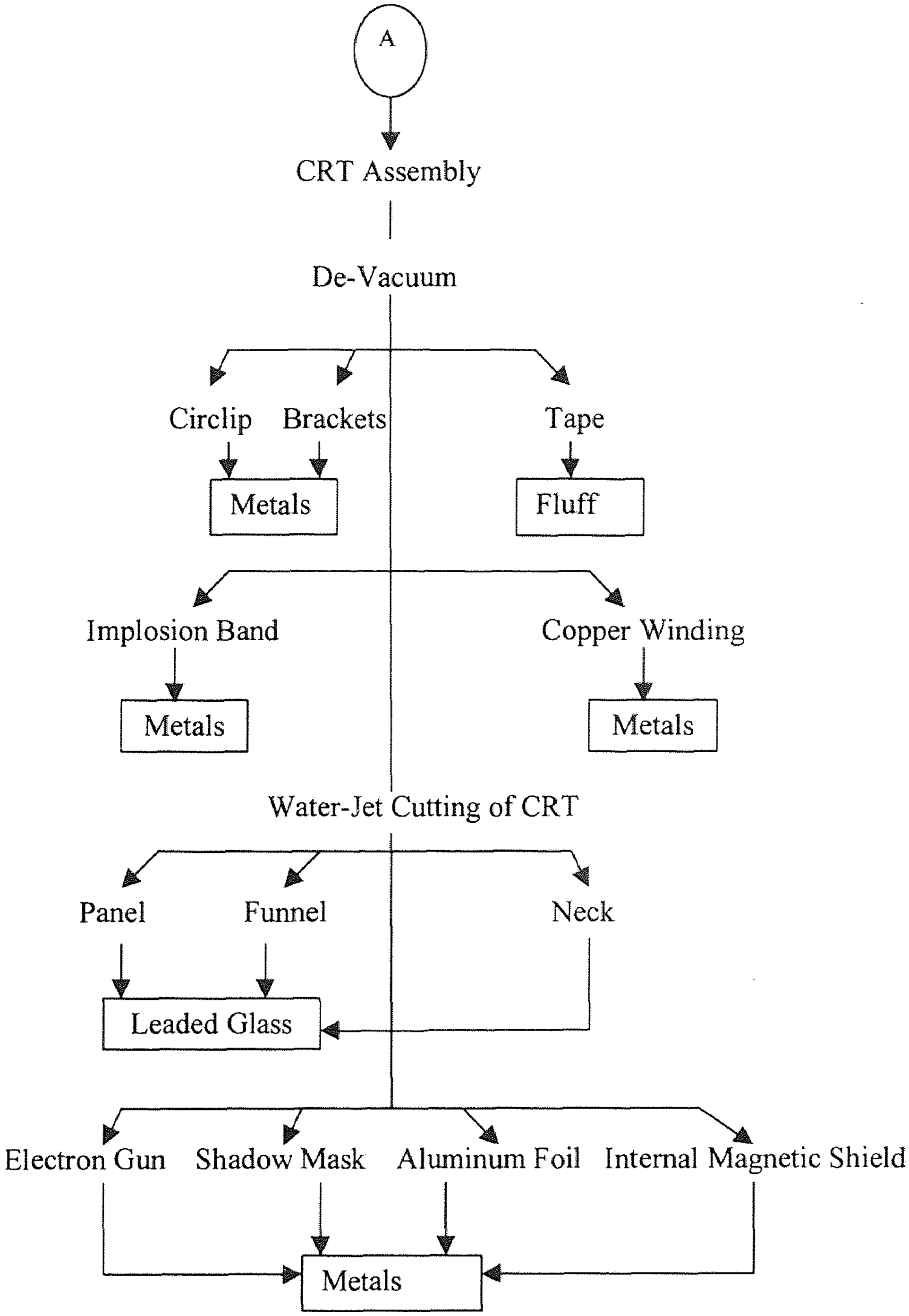


Figure 6.4 (Cont.) Reverse Fishbone Diagram 3

6.5.3 Analysis of the Reverse Fishbone Diagram

Analysis of the reverse fishbone diagram helps designers and demanufacturers in many areas. It essentially permits the designer to generate qualitative and quantitative information about the designs performance under product retirement scenarios. Used together with disassembly time data and subassembly reprocessing cost projections, fishbone analysis can provide the designer and also the demanufacturer with early guidance in following areas,

- Retirement clump identification/refinement
- Projections of fate category load levels – matching retirement scenario with market demand of reused components and recycled materials
- Identification of potential improvements in disassembly steps and procedures – employ a fixture, tool, or redesign a part.
- To identify inter-component connections that pose disassembly difficulties
- Retirement cost/revenue stream projections

Analysis:

The reverse fishbone diagram shown in Figure 6.2 illustrates many interesting points about the end-of-life options for a disassembled television. The first more detailed RFBD can be analyzed as follows:

- For the television that was disassembled, five main fate categories were identified. These are grade 'A1' bin for metals, grade 'A2' bin for mixed plastics, grade 'A3' bin for leaded glass, grade 'B' bin for PCB's, grade 'C' bin for commingled or contaminated materials, and grade 'D' bin for fluff, as indicated in Table 6.3.

- As far as matching the retirement scenario with market demand of reused components and reengineered materials is concerned, there were no components identified in the disassembled television that can be reused. One reason for this might be the year of manufacture of the television, which makes its components obsolete from the current televisions. So, consequently no components in the television are recovered for reuse. All the materials identified, except for mixed plastic are valuable and have good market demand for their secondary production and hence should be recovered. The mixed plastics can also be reengineered, but new markets should be developed for such kind of plastics. This conclusion was reached by studying the market conditions and demand for scrap materials. The market demand and prices for scrap materials were taken from scrap metal dealers, demanufacturers, and also verified on the internet.
- The back cover, channel control knobs, antenna, its chord and connections can be disassembled simultaneously. These components are sequence independent. So, the television disassembly need not start by first removing the antenna and chord, as indicated in the disassembly diagram, but the above three components can be removed simultaneously.
- Analyzing on similar lines, the remaining of the reverse fishbone diagram indicates disassembly operations for various sub-assemblies and components that can be carried out simultaneously. This can be compared with the disassembly diagram, which is truly sequential. The sub-assemblies and components that can be disassembled at the same time are therefore shown on the same horizontal level.

- Once the CRT and the channel assembly are removed from the television, they can be disassembled further at the same time. The CRT needs to be opened if the demanufacturer wants to disassemble it further, for recovering the leaded glass and other metals such as steel, aluminum, and copper. These materials can be reengineered to reduce the environmental burdens over the television's lifecycle and also to reduce the virgin raw material requirement. This links with the inventory analysis of these materials in the secondary production, where these materials enter the generic process model either at the intermediate or at the final processing stage.
- It is not necessary to have a special kind of fixture for disassembling the television. But for cutting the CRT by water jet machining, a fixture is necessary.
- Finally, the level of disassembly should be analyzed, which is done in the next section.

6.6 Cost Effectiveness Analysis

Every demanufacturer has to decide the level of disassembly that gives maximum profits. This is very important because disassembling the complete product and its sub-assemblies until the level that no further disassembly is possible is not always economical. Theoretically the demanufacurer should go to the level where no further disassembly is possible, but practically it never works due to economical and technological constraints. The level of disassembly depends upon the end-fate objective of the product, its subassemblies, and the components.

Another most important factor that drives the cost of disassembly is the time required for the disassembly operation. All the factors such as level of disassembly and economics of disassembly are directly related to the time required for the disassembly operation. As the level of disassembly increases, the time required for disassembling increases. Also as the level of disassembly increases more pure materials are recovered yielding higher values. The balance of these two factors is very important and dominates the economics of the entire demanufacturing process.

Cost effectiveness analysis is one value analysis tool, which helps in striking this balance between the level of disassembly and the time required for the disassembly operation. Cost effectiveness analysis evaluates the economics of selected end-fate scenarios in terms of the time and the current market value of the recovered material. This analysis is done, by generating a sequence of end-fate scenarios and associated reverse fishbone diagrams, then comparing the effectiveness of each of them. The different reverse fishbone diagrams primarily show the different disassembly process plans that can be implemented to disassembly the same product. This is where the non-uniqueness of the reverse fishbone diagram lies. There can be more than one reverse fishbone diagram for the same product; consequently which is the best and yields the maximum profits can be decided.

6.6.1 Procedure for Cost Effectiveness Analysis

Cost effectiveness analysis is based on the value of materials recovered and the time required for that disassembly process. The following procedure is used for calculating the cost effectiveness of demanufacturing a given product:

- The first step is to define a sequence of end-fate scenarios and generate the associated reverse fishbone diagrams.

- The second step is to identify all the materials in the product and then classify them in terms of the bins described earlier.
- Then all the individual subassemblies, components, and materials are weighted.
- For each material type, the weight of materials from a particular reverse fishbone diagram are added to get the total weight of that particular material in the product. If a subassembly is not to be disassembled then the weight of the entire subassembly is taken. If this subassembly contains different materials then it is classified as commingled or dirty material. Similarly, all the subassemblies and materials are weighted and added.
- After this, the time required for recovering or disassembling this subassemblies and materials is added to get the total time for removing a particular subassembly or recovering a particular material.
- Then the market rate for all the materials is obtained and multiplied by the weight of the material to get the total market value of that material. For example assume steel, and copper are recovered from the product after disassembly. If the weight of pure steel recovered is 5 pounds and the current market rate is $ 0.05 per pound, then the value of the pure steel will be $ 0.25. However, if the subassembly contains a mixture of steel and some copper, then value will be substantially less since the market price for commingled steel is half the price of pure.
- Then the individual times required for a subassembly or a material are also added to get the total time for the entire disassembly process for that particular reverse fishbone diagram. For example, time required for recovering all the steel from the product by following RFBD1 disassembly process plan, is 885 time units.

- Another important task is to determine the weight of the fluff that remains after the materials are assigned their fate categories. The fluff is normally landfilled and hence a landfill cost is associated with this activity. So, the landfill cost for the fluff should be subtracted from the total value of materials recovered. The tipping fee here is assumed as $ 75 / ton of fluff landfilled.
- Now cost effectiveness of an entire disassembly process can be calculated by using the following formula:

$$\text{Cost Effectiveness} = (\text{Value of materials} - \text{landfill costs}) \;/\; \text{Time}$$

where,

Value of materials = the total value of a material,

Time = total time required for recovering all of the material (of one type) from the product.

The cost effectiveness number is calculated following the above procedure for the three reverse fishbone diagrams. The three reverse fishbone diagrams were generated with three end-fate objectives in mind. The end-fate objectives for the three reverse fishbone diagrams are as follows:

- RFBD1 = Disassembly to the highest level to recover materials as pure as possible
- RFBD2 = Disassembly to the level of removing major subassemblies and resulting basic materials
- RFBD3 = Disassembly to recover the CRT from the television and then disassemble the CRT

Table 6.4 shows the current market values for the scrap materials. Table 6.5, Table 6.6, and Table 6.7 show the calculations and total values obtained from these three reverse fishbone diagrams.

Table 6.4 Current Market Values for Scrap Materials [28]

Material	Pure state ($/lb)	Commingled state ($/lb)	Dirty state ($/lb)
Steel	0.045	0.030	0.020
Aluminum	0.40	0.005	0.20
Copper	0.85	0.05 and up	0.50
Plastic	0.0040	0.025	-
PCB	0.005 to 50	-	-
Leaded Glass	-	100 – 350 ($ / ton)	-

These scrap material values were obtained from a scrap metal dealer and a demanufacturer. There is actually no value for mixed or commingled plastic, but for the sake of calculations a very low value is considered. The "dirty" category differs from the commingled one in that commingled is considered to be the metal contaminated by an alloy or very little quantity of other metals. But "dirty" refers to the contamination by totally different materials; for example, contamination of steel subassembly with small, but significant, amounts of plastic components in it. The PCB value indicated depends upon the gold content present in the PCB. The television PCB and the CRT PCB does not contain high value materials that can be recovered, and hence a very low value of 10 cents per pound is considered for the printed circuit board calculations.

Following are the calculations and analyses of the three reverse fishbone diagrams with their respective tables:

Analysis of RFBD1:

The first reverse fishbone diagram (RFBD1) is generated with the end-fate objective of recovering maximum quantity of pure materials. Table 6.5 shows the calculations for this category followed by its analysis.

Table 6.5 Cost Effectiveness Analysis for RFBD1: Total Disassembly to Maximize Purity of Materials

Bin	Weight (lbs)	$ / lb	$ Value	Total Time for a material (hours)	Contents of the bin
Steel	3.68	0.045	0.166	0.25	Pure steel
Aluminum	0.01	0.4	0.004	0.01	Pure aluminum
Copper	1.1025	0.5	0.551	0.38	Dirty copper

Table 6.5 (Cont.) Cost Effectiveness Analysis for RFBD1: Total Disassembly to Maximize Purity of Materials

Mixed Plastic	5.20	0.025	0.13	0.11	Commingled Plastics
PCB	0.687	0.1	0.0687	0.08	Low value
Leaded-glass	0.00571 (tons)	200/ton	1.142	0.50	Commingled (for monochrome)

The total value of materials recovered by using the reverse fishbone diagram 1 = \$ 2.062.

The total time required for the entire process = 1.33 hours.

Therefore, the cost effectiveness for RFBD1 is

$$\text{Cost Effectiveness} = (2.062 - 0.0 / 1.33)$$

$$= \$\ 1.55 / \text{hr}$$

It was observed from this analysis that the leaded glass has the highest value and hence should be recovered effectively. So considering this, the other two reverse fishbone diagrams, with different end-fate objectives, were generated to evaluate their effectiveness in recovering the leaded glass from the CRT.

Analysis of RFBD2:

This second reverse fishbone diagram (RFBD2) is generated to recover the leaded glass, subassemblies, and some purity of materials. Its calculations are shown in Table 6.6 and analysis is shown after that.

Table 6.6 Cost Effectiveness Analysis for RFBD2: Recovery of Subassemblies and Some Materials

Bin	Weight (lbs)	$ / lb	$ Value	Total Time For a material	Contents of the bin
Steel	3.71	0.02	0.0742	0.20	Dirty steel
Aluminum	0.01	0.4	0.004	0.01	Pure aluminum
Copper	1.08	0.5	0.54	0.02	Dirty copper
Mixed Plastic	4.93	0.025	0.123	0.08	Commingled
PCB	1.00	0.10	0.10	0.04	Low value
Leaded-glass	0.00571 (tons)	200/ton	1.142	0.50	Commingled (for monochrome)

The total value of materials recovered by using the reverse fishbone diagram 2 = $ 1.981.

The total time required for the entire process = 0.85 hours.

Therefore, the cost effectiveness for RFBD2 is

$$\text{Cost Effectiveness} = (1.981 - 0.0 / 0.85)$$

$$= \$\,2.33 / \text{hr.}$$

As observed from this analysis, it was concluded that one more reverse fishbone diagram should be generated to recover only CRT and compare with the other two diagrams for cost effectiveness.

Analysis of RFBD3:

The third reverse fishbone diagram (RFBD3) was generated to recover only the CRT from the entire television. So, the television was disassembled only to the level that the CRT is removed from it. Table 6.7 shows the calculations for this RFBD followed by its analysis. After removing the CRT from the television, the remaining subassemblies, components, and materials are discarded as fluff in the landfill. This has to be done because this mixed material does not have any value and hence a landfill cost is associated with it as discussed after Table 6.7. The time indicated for the recovery of the materials from the CRT and the CRT itself is in hours.

Note that in all the three reverse fishbone diagrams, the numbers indicated are rounded off to the nearest integer.

Table 6.7 Cost Effectiveness Analysis for RFBD3: Recovery of only CRT

Bin	Weight (lbs)	$ / lb	$ Value	Total Time for a material (hour)	Contents of the bin
Steel	1.470	0.045	0.089	0.10	Dirty steel
Aluminum	0.01	0.40	0.004	0.01	Pure aluminum
Copper	0.758	0.50	0.37	0.02	Dirty copper
Mixed Plastic	4.927	0.005	0.024	0.02	Commingled
PCB	0.09	0.10	0.009	0.02	Low value
Leaded-glass	0.00571 (tons)	200/ton	1.14	0.50	Commingled (for monochrome)

The total value of materials recovered by using the reverse fishbone diagram 3 = $ 1.63.

The total time required for the entire process = 0.67 hours.

The other two scenarios recover mainly all materials therefore no landfill costs are associated with them. But in this third scenario, after the CRT is removed from the television, the remaining subassemblies, and materials are treated as fluff. A fluff is a mixture of plastic, steel, and copper, and has to be landfilled. There is a cost associated with this landfilling activity. And so the cost of landfilling such a fluff can be calculated as follows:

Total Weight of Fluff = 0.00354 tons

Assuming the tipping fee = \$ 75 / ton

The cost of Landfilling = 0.004 X 75

= \$ 0.30

Therefore, the cost effectiveness for RFBD3 is

Cost Effectiveness = (1.63 – 0.30 / 0.67)

= \$ 1.9 / hr.

It was observed that this value is more than RFBD1 but less than RFBD2.

Analysis of the Cost Effectiveness Values:

There are several interesting points to note from these three reverse fishbone diagram analyses as discussed below.

- The cost effectiveness increases from the first RFBD but the third RFBD has again less value than the second reverse fishbone diagram. This trend in increase from RFBD 1 to RFBD 2 can be attributed to the decrease in disassembly time, as the end-fate objective becomes limited to recovering certain particular subassemblies or materials. But as seen from RFBD 3, if the end-fate objective is to recover only the CRT, then again the cost effectiveness value decreases.
- Comparing the first two RFBD's the value of steel and the time required to recover it decreases from RFBD1 to RFBD2. But the percentage decrease in value is much lower than that compared to time. So, it is still profitable to recover less steel and save time in recovering that extra amount. RFBD2 clearly overrules the other two, because

though the value is less, there is no land cost associated with it and hence proves more profitable than RFBD3.

- The aluminum is not affected at all in all the three reverse fishbone diagrams, because the only aluminum present in the entire television was in the aluminum foil used in the CRT and in all the three disassembly process plans it has to be removed to recover the leaded glass.
- The plastics in the television has no value, first of all because there are different types of plastics used in the entire television, ranging from Polystyrene to ABS to Polyacetal. So, it can be concluded, by this cost effectiveness analysis that, efforts to recover plastics from the television at the current market conditions is not economical.
- The main inference that can be drawn from this analysis is that, the actual value is only in the leaded glass, from the entire television. As seen from the three cost effectiveness tables, if the value of leaded glass is subtracted from the total value then the cost effectiveness is almost zero as all other values are in decimals.
- And especially in RFBD3, which is generated only for recovery of the leaded glass, the other materials have no value. But these other materials are required to be removed, to reach and recover the CRT and the leaded glass.
- Moreover in RFBD3 there are no toxic materials present in the remaining fluff. But the fluff has to be landfilled as discussed earlier and its cost makes RFBD3 analysis uneconomical.
- Hence, after studying all the reverse fishbone diagrams generated for three end-fate objectives, it can be concluded that the second reverse fishbone diagram and

consequently the disassembly process associated with it should be adopted for the entire demanufacturing to be profitable and economical.

- The results of the cost effectiveness analysis for the three reverse fishbone diagrams are summarized in Table 5.8 below.

Table 6.8 Summary of Results for the Three Reverse Fishbone Diagrams

RFBD Number	Value of Recovered Materials ($)	Time Required for Recovery (Hr)	Cost Effectiveness Value ($/hr)
RFBD 1	2.06	1.33	1.55
RFBD 2	1.98	0.85	2.33
RFBD 3	1.33	0.67	1.9

Lastly, it can be concluded from Table 6.8, there are many other factors, which also play an important role in the cost effectiveness analysis for any product. The labor cost, the transportation costs are not included in this particular analysis, and hence the actual costs would be different than those indicated in Table 6.8.

CHAPTER 7

CONCLUSION

This chapter summarizes the results and conclusions of the entire research conducted in this thesis. The first and the second section in this chapter summarize the results obtained from the inventory analysis and the demanufacturing study, respectively. The third section draws general conclusions from this entire research. The final section recommends the areas for future research and improvements.

7.1 Summary of Inventory Analysis

The type of materials used in a product affects its environmental performance through its lifecycle. The selection of materials, is therefore, very critical in designing any product. There are several interesting conclusions to be drawn from the LCI of materials conducted. These are as follows:

- It was observed that the generic process model developed for the primary and secondary production of the materials is applicable to all the materials. The primary materials found – CRT's - steel, aluminum, copper, lead, and even leaded-glass - are accommodated in this model. In addition, preliminary results indicate that the model also accommodates the production of plastics. The secondary production of materials from recycled feedstock is directly reflected in the model giving an immediate indication of the importance of reengineering the materials to reduce the environmental burdens associated with raw material extraction and pre-processing. Consequently development of such a generic process model for the primary and secondary production of materials strengthens the material database and provides a consistent framework for evaluating material substitution options.

- The inventory charts for the production of steel, aluminum, copper, lead , and leaded-glass were developed based on published and available data compiled from various sources.
- Although a formal impact assessment study was not conducted, the environmental issues associated with the production of these materials were addressed and presented in chapter 5. The Gross Energy Requirements (GER) per ton for the primary production of each material was calculated and is presented below in Table 7.1. Table 7.1 is truly a summary comparison of the GER for the primary materials. The energy values in Table 7.1 are rounded off to the nearest integer.
- As observed from Table 7.1, aluminum consumes the maximum energy for its production and steel consumes the least energy. But secondary production of aluminum requires only 5-7 percent of the energy of primary production hence, aluminum recycling is very successful and its environmental burdens are much less. Next to aluminum, copper consumes the largest amount of energy, hence, secondary production of copper should be encouraged and expanded over its present low level. Similarly, from the generic process models for these materials and observing their energy requirements and environmental burdens, tremendous opportunities exist for reengineering these materials.

Table 7.1 Gross Energy Requirement for the Primary Production of Materials

Type of Energy	Steel	Aluminum	Copper	Lead	Leaded-Glass
Electricity (KWh)	136	15,868	2,924	85	
Fuel (MBTU)			18 (5,276 KWh)	15 (4,397 KWh)	
Process Heat (MJ)	1,901 (528 KWh)	41,120 (11,423 KWh)			10,703 (2,973 KWh)
Total (KWh)	664	27,291	8,200	4,482	2,973

- There are various co-products generated during the production of these materials. But the allocation of co-products is very complex, as several factors play a key role in the production of these co-products. A typical co-product identified is sulfuric acid, which is produced from the sulfur dioxide emissions during the primary production of copper.
- Another important observation was that lead produces emissions of lead oxides and compounds, during its production, which are hazardous concern to the health and

safety of workers. Other hazardous emissions are from aluminum production. These are the CF_4 and the C_2F_6 emissions generated during the aluminum smelting process.

- Based on the LCI of these materials, it can be concluded that the production of feedstock materials are an important stage in the lifecycle of a manufactured product and contribute significantly to the environmental burdens of that product. The extrinsic material properties identified earlier in Chapter 5 of this thesis should also be addressed upfront during the design stage, along with the intrinsic properties.
- The results obtained for the environmental burden of a CRT from its raw material extraction stage through its production stage are presented in section 5.9 of Chapter 5, with detailed tables. The main results are summarized below.

The total environmental burdens of a CRT from raw material extraction through production is:

1. Total Solid Wastes generated = 338 Kgs
2. Total Air Emissions generated = 4 kgs
3. Total Energy Consumed = 92 KWh
4. Total Energy Consumed during the Use phase = 800 KWh (Assumed for 10 years)

As observed from this summary, the maximum consumption of energy is during the use phase of a CRT. There is no other data available for comparing the environmental burdens associated with the solid wastes and the air emissions, but from Table 7.1 it is quite evident that the solid wastes generated are substantial and steps should be taken towards reducing them. Especially the water waste represents 81 % of the solid wastes generated and should be examined further.

7.2 Summary of the Demanufacturing Study

The demanufacturing study yielded several very interesting results and motivation for further research in this relatively new area.

- From the analysis of the disassembly procedure it was concluded that the disassembly process may not be completely standardized and automated. The main reason for this is the complexity involved in the process and the decision of the demanufacturer regarding the end-fate scenarios of the recovered material.
- Although the disassembly diagram shows the sequential disassembly of the television, it is concluded that there are operations in the disassembly process that can be done simultaneously. These operations are reflected in the reverse fishbone diagrams generated for the three end-fate scenarios discussed in the demanufacturing chapter. It can also be concluded that the product should be designed such that there is minimum dependency between components. This ensures more simultaneous disassembly operations and thus reduces the disassembly time and effort; and, hence sequence dependency and independency play a important role in the disassembly process.
- The reverse fishbone diagrams truly indicate the graphical representation of the disassembly process, and helped to identify the potential problems and improvements needed, which are indicated in the demanufacturing chapter, that can be incorporated to improve the entire disassembly process. It is concluded that the reverse fishbone

diagram technique is an effective tool in analyzing the disassembly operation of any product.

- The cost effectiveness analysis was performed not to compare different end-of-life options for a television, but to compare different end-fate scenarios for the materials recovered, after the disassembly operation.
- The cost effectiveness analysis performed indicated that the level of disassembly, the time required for the individual disassembly operations within the entire assembly and consequently for the complete product and the end-fate scenarios for the recovered materials are interrelated. For economical and profitable operation of the demanufacturing industry, a trade off between these factors is essential. The demanufacturer may not be able to improve only one of these to achieve profits. Because increasing the level of disassembly to recover more pure materials, requires more time and increases the labor cost associated with it. On the other hand, reducing the time by recovering less amount of purer, high valued materials, does not give enough pay back for demanufacturing to be economically viable. So, it can be concluded that the demanufacturer should decide the end-fate scenarios before the disassembly operation starts and accordingly adopt a disassembly process and reverse fishbone diagram. This is a kind of disassembling planning, which is done by knowing earlier the end-fate of the subassemblies, components, and the materials that represent the highest value are to be recovered from the disassembly process. Demonstrate here was the use and effectiveness of the reverse fishbone diagram using a discarded television as an example.

- Finally it was observed that, the second end-fate scenario of recovering some pure materials and the CRT leaded-glass is more profitable and economical, compared to recovering all pure materials, by disassembling the television till the lowest level, or recovering the CRT glass and landfilling the remaining carcass. The cost effectiveness for the recovery of only the CRT from the television also did not vary much from the first end-fate scenario.
- One of the main conclusions from the reverse fishbone diagrams and the cost effectiveness for the television is that the main value lies in the CRT and its leaded glass. But the other subassemblies should be removed and sorted also for recovering the commingled and dirty materials.
- It is very important to note here that the cost effectiveness analysis performed is purely on the basis of an example and the numbers obtained do not necessarily reflect current practice. The basic conclusions drawn from this example are extendable to actual applications.

7.3 General Conclusions

There are several issues related to the Lifecycle Analysis (LCA) field and are summarized as follows:

- The traditional lifecycle approach as applied to the inventory of materials proves to be beneficial in assessing the environmental impacts, even though a complete impact assessment study is not conducted.

- A new approach called Multi-Lifecycle Assessment (MLCA) much more similar to LCA was developed. MLCA emphasized a cradle-to-cradle approach rather than traditional cradle-to-grave approach of LCA.
- LCA is more of an input and output analysis tool, rather than a complete environmental impact assessment tool, as regards to its current status.
- LCA practitioners should take special care in performing the inventory analysis, due to the variations and confidence in the data from different sources. One suggestion is to conduct a sensitivity analysis to determine which data is most important and then focus on improving the quality of this data.
- Finally, conducting LCA is a very complex and exceedingly detailed process. However, with the help of more publicly available, high quality data and further improvements in the assessment stages, LCA should be used as a tool to create more environmental friendly processes and products.
- Lastly, while using the Toxic Release Inventory Database (TRI) it was observed that there are several issues, which restrict the TRI user from extracting useful information. The search in the TRI database is very cumbersome and difficult. The TRI database should be modified, by which the users may be able to easily use it and thus gather more meaningful toxic release data, which is very important in calculating the environmental burdens of a product.

7.4 Future Recommendations and Scope for Research

- There are still some data gaps in the inventory for some materials that need to be completed. Especially, the data for the environmental burden of lead oxide production and leaded-glass is important to obtain.
- A formalized impact assessment study should be conducted based on the inventory data developed here to assess the environmental impacts of the CRT.
- The MLCA conducted for the CRT should be extended further to include the environmental impacts from other stages of the lifecycle of the CRT, including the usage, reengineering, and disposal stage.
- Steps should be taken to access and search the TRI database more efficiently and extract meaningful data effectively.
- A formal demanufacturing process model should be generated and efforts should be implemented towards developing the infrastructure and practices for a successful demanufacturing.
- The demanufacturer should be encouraged to adapt planning tools to disassemble the product and recover components and materials efficiently and effectively.

APPENDIX A

INVENTORY CHARTS

Appendix A contains the inventory charts for the materials analyzed in chapter 5 of this thesis. The values indicated for the raw materials, output, slag, emissions, and process wastes are in tons. The energy values are in KiloWatt Hours (KWh), Million British Thermal Units (MBTU), and Mega Joules (MJ) depending upon the type of energy such as electricity, fuel, or process heat respectively.

The charts are in the following order:

A.1 Inventory chart for steel production
A.2 Inventory chart for aluminum production
A.3 Inventory chart for copper production
A.4 Inventory chart for lead production
A.5 Inventory chart for funnel leaded-glass production
A.6 Inventory chart for neck leaded-glass production
A.7 Inventory chart for panel leaded-glass production

Table A.1 Inventory Chart for Primary Steel Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Coal Raw limestone Iron Ore	0.7 0.25 2.8	Fuel + Electricity	3.6 MJ	Mining, Extraction, Beneficiation, Sinter Production.	Sinter (Coke – 0.5 + limestone – 0.25 + Iron Oxide – 1.4)			Mineral wastes – 3.5
2	Air Dolomite	1.8 0.23	Fuel Electricity	1411 MJ 42 kWh	Pig Iron production and hot metal desulfurization	Molten Pig Iron – 0.775	CaO + SiO_2 + Al_2O_3 – 0.3	CO_2 – 1.44 NO_X – 0.022 SO_2 – 0.022 BOG – 3.0	Dust particulate – 0.0013
3	Scrap steel Water FeMn Refractory FeSi Fluorospar Aluminum	0.364 40Kgl. 0.011 0.0023 0.001 0.0005 0.0005	Fuel Electricity	486 MJ 94 kWh	Basic Oxygen Furnace (steelmaking)	Raw steel - 1.00	Si + MnO + P_2O_5 + FeO + S + Lime – 0.11	CO – 0.001 CO_2 – 1.109	

Table A.2 Inventory Chart for Primary Aluminum Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Bauxite Sand	4.00	Fuel		Mining, Grinding, Crushing, Washing & Drying.	Bauxite Ore - 3.77			
2	Limestone Caustic Soda	0.076 0.077	Heat Electricity	30.65 GJ 424 kWh	Bayer (Bauxite Refining, Alumina Clarification, Precipitation	Alumina - 1.93	Red Mud & Sludge - 1.9	Particulates - 0.025	Waste water containing starch & sand
3	Cryolite Al-flouride Carbon Anodes	0.03 0.04 0.51	Heat Electricity	10.47 GJ 15444 kWh	Hall - Heroult Process (Electrolysis)	Aluminum Ingot - 1.00	Spent Potliner – 0.0153	CO - 0.79 (0.338C) CO_2 - 0.65 (0.172C) Fluoride - 0.02 (0.018HF & 0.002 part) Particulates (HF) - 0.045 (0.04 Al, 0.04 F, 0.01 Na)	

Table A.3 Inventory Chart for Primary Copper Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Copper Ore Lime Steel Floatation Reagents	164.82 0.396 0.157 0.012	Electricity	2703 kWh	Mining, Beneficiation, Concentration, Floatation, Leaching & Roasting	Copper conc. - 4.121	Tailings (0.1385 Cu.) - 160.7		Floatation Waste waters
2	Limestone Silica Oxygen	0.256 0.820	Fuel	15.26 MBTU	Smelting - Calcine Converting - Cu. Matte Fire Refining - Blister Cu.	Copper Anode - 1.025	SiO_2, FeO, CaO, Al_2O_3, Cu, MgO - 3.203	SO_2 - 0.2765 Particulates - 0.011 Gas, Dust (0.35% Cu.) - 0.334	
3	$CuSO_4$ + H_2SO_4	1.302	Fuel Electricity	2.65 MBTU 221 kWh	Electrolitic Refining (Electrolisis)	Copper Cathode - 1.000	Metallic Impurities - 0.018 Anode mud (25% Cu.) - 0.006	Particulates	Copper Salt - 0.0007

Table A.4 Inventory Chart for Primary Lead Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Galena		Fuel + Heat	10.33 MBTU	Mining, Crushing, Beneficiation, and Froth Flotation Sintering	Sintered Lead		SO_2 Particulate Matter (Pb, Cd)	
	Limestone	0.12							
	Iron ore	0.07							
	Sand	0.09							
2	Coke	0.23	Heat	1.71 MBTU	Smelting and Drossing – sintered lead is converted to lead bullion	Lead Bullion	Slag (Zn, Fe, Si, Cu, Lime)	SO_2 Particulate Matter (Pb, Cd)	
	Soda ash	0.01							
	Sulfur	0.002	Electricity	46.8 KWh					
3	Zn spelter	0.0056	Heat	3.17 MBTU	Refining – 1. Softening 2. Parke's process 3. Final refining	Lead metal	Slag is in terms of other metals which are recovered		
	Calcium	0.00066							
	Magnesium	0.00173	Electricity	38 KWh					
	Caustic Soda	0.001							
	Niter ($NaNO_3$)	0.00025							

Table A.5 Inventory Chart for Primary Funnel Leaded-Glass Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Lead Oxygen		Heat	4172.3 MJ	Furnace operation	Litharge		Lead compounds Lead oxides	
2	Silica Alumina K_2CO_3 Na_2CO_3 Whiting Talc PbO SB_2O_3	1.001 0.0371 0.2345 0.204 0.125 0.161 0.460 0.0015	Heat	5623.6 MJ	Glass furnace operation	Leaded Glass – 1 ton	Cullets	Carbon dioxide Lead oxides	

Table A.6 Inventory Chart for Primary Neck Leaded-Glass Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Lead Oxygen		Heat	4172.3 MJ	Furnace operation	Litharge		Lead compounds Lead oxides	
2	Silica Alumina K_2CO_3 Na_2CO_3 PbO SB_2O_3 $SRCO_3$	1.001 0.0371 0.2345 0.204 0.460 0.0015 0.142	Heat	5351.5 MJ	Glass furnace operation	Leaded Glass – 1 ton	Cullets	Carbon dioxide Lead oxides	

Table A.7 Inventory Chart for Primary Panel Leaded-Glass Production

No.	Input				Process	Output			
	Raw Material	Qty.	Energy	Qty.		Product	Slag	Air Emissions	Process Wastes
1	Lead Oxygen		Heat	4172.3 MJ	Furnace operation	Litharge		Lead compounds Lead oxides	
2	Silica	1.146	Heat	6530.6 MJ	Glass furnace operation	Leaded Glass – 1 ton	Cullets	Carbon dioxide Lead oxides	
	K_2CO_3	0.267							
	Na_2CO_3	0.218							
	Whiting	0.0589							
	Na Feldspar	0.186							
	PbO	0.0532							
	$SrCO_3$	0.293							
	SB_2O_3	0.0108							
	$BaCO_3$	0.0645							
	CeO_2	0.0032							

3

APPENDIX B

CRT WATER JET CUTTING PHOTOGRAPHS

Appendix B contains the photographs taken while cutting the CRT by the water jet machining process.

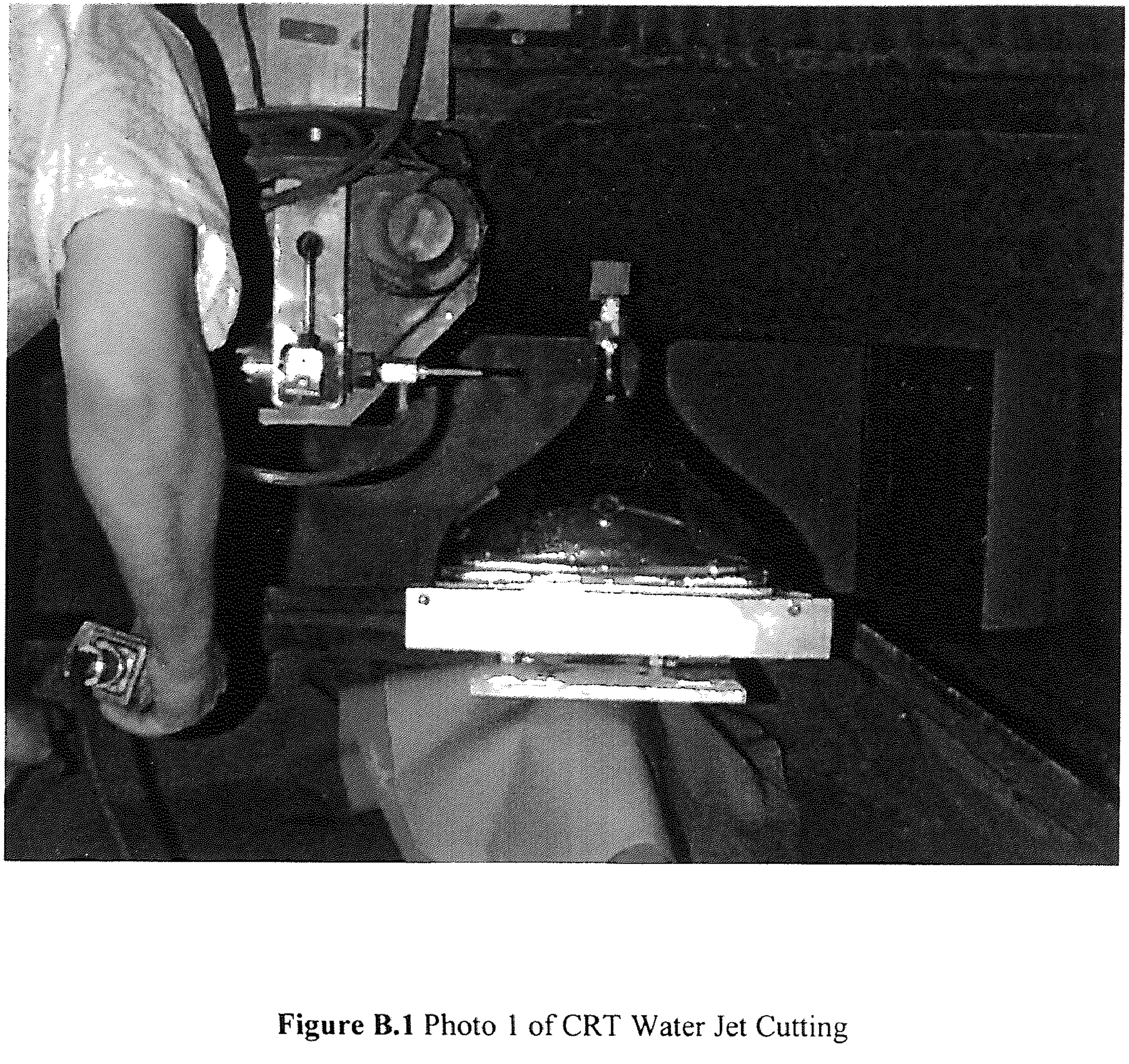


Figure B.1 Photo 1 of CRT Water Jet Cutting

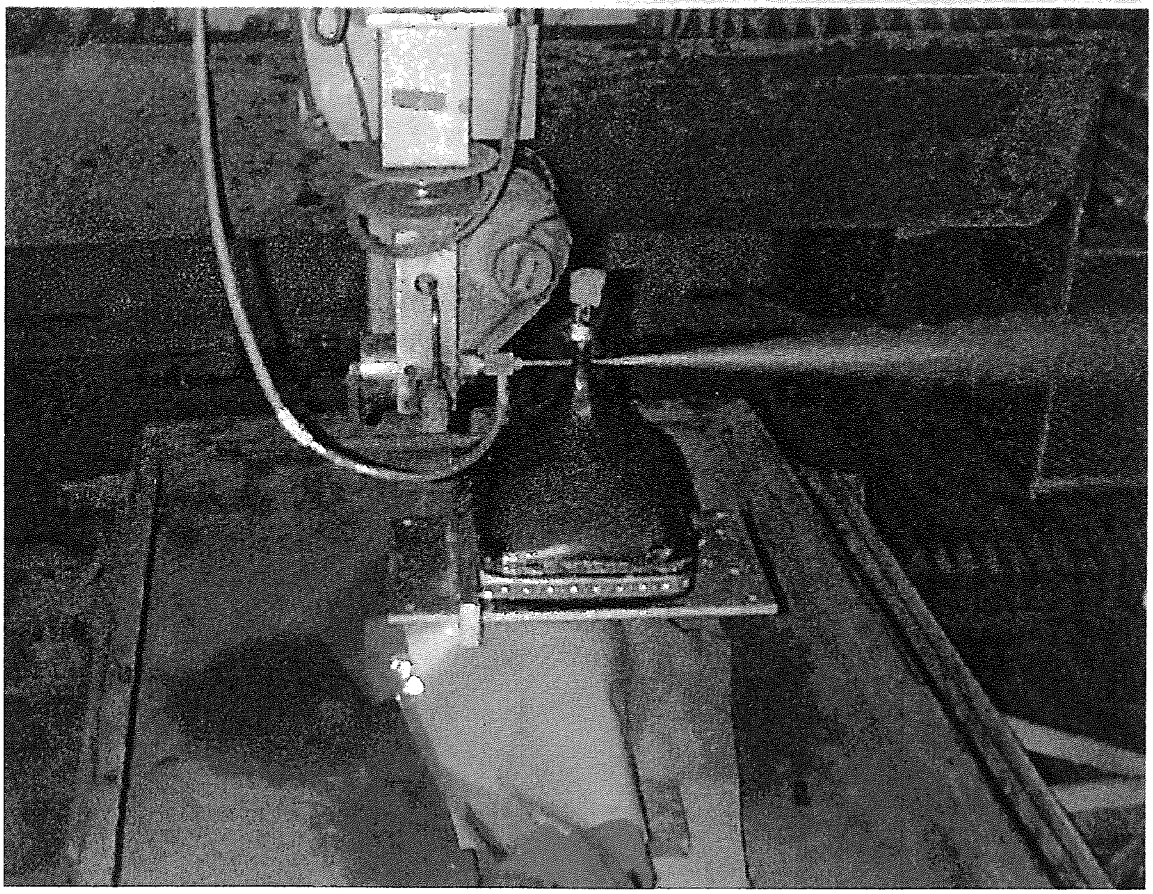


Figure B.2 Photo 2 of CRT Water Jet Cutting

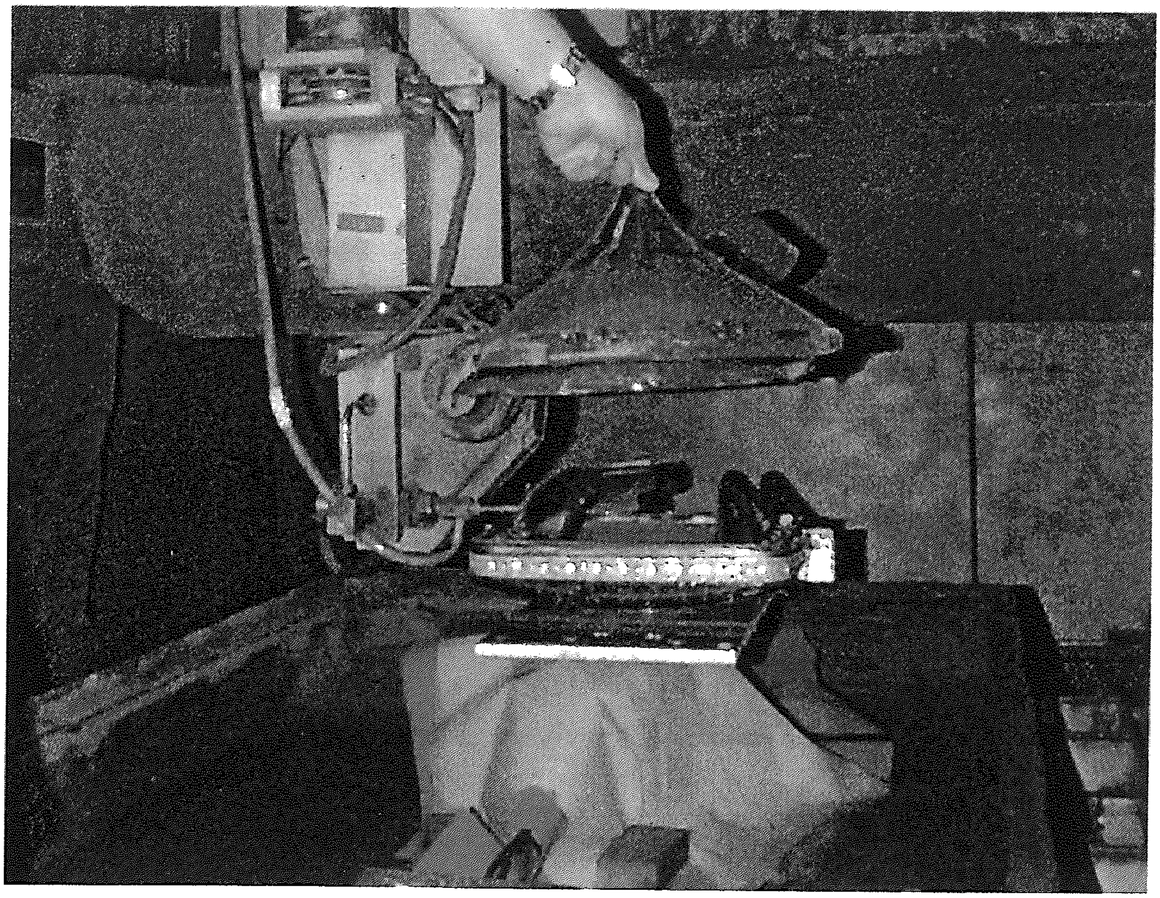


Figure B.3 Photo 3 of CRT Water Jet Cutting

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