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TECHNICAL REPORT:

ENVIRONMENT PROTECTION IN THE DOWNSTREAM PETROCHEMICAL INDUSTRIES*

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* The views expressed in this paper are those of the author and do not necessarily reflect the views of the Secretariat of UNIDO. This document has not been edited.

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1.0 INTRODUCTION

Environmental considerations have become an integral part of many manufacturing operations around the world. Some industries, such as the steel industry, have wrestled with environmental considerations for several decades primarily because of the large volumes of pollutants they create. On the opposite extreme, industries that only ten years ago would not have imagined being subject to environmental laws are now finding themselves involved. Even an activity such as the disposal of a hazardous material, operation of fuel burning equipment, or discharge of a waste water with organic material can be sufficient to warrant environmental considerations.

The downstream petrochemical industry includes many operations for which there is an opportunity for environmental conservation. Discharges to air, water, and solid waste from such industries as rubber manufacturing, plastics processing, and synthetic fibers manufacturing may be reduced via waste reduction or pollution control. Environmental issues will present enormous challenges to the synthetic rubber producers in the 1990s and beyond, according to experts who spoke at the 32nd annual general meeting of the International Institute of Synthetic Rubber Producers. (Moore, 1991)

This document provides an introduction to the types of environmental challenges faced by the downstream petrochemical industries currently and in the near future. Section 2 contains information on the types of wastes and pollutants generated from a variety of operations in the downstream petrochemical industry. Section 3 discusses some regulatory drivers in place to encourage waste minimization and pollution control. Some short-term, medium-term, and long-term options for environmental management are also discussed in Section 3. In Section 4, the economics of environmental management are addressed, including a discussion of the shortfalls of methods to assign profits and costs to environmental conservation and degradation. Section 5 outlines some of the tools to be used to describe the environmental issues facing a facility and those tools to be used in achieving environmental conservation goals. Some of these tools can be incorporated into the culture and day-to-day operations of a company. Other tools may require dedicated staff or assistance from outside the company for implementation. Section 6 contains specific references used to develop this document.

2.0 WASTE SOURCES AND POLLUTANTS GENERATED

The first step in developing an environmental conservation program must be to take an inventory of the waste generated by an operation. The inventory must be conducted methodically to ensure that all wastes are identified. Approaches to the inventory may include one or more of the following.

1. **Grid.** Divide an entire facility (areas including indoor and outdoor production, treatment, storage, loading and unloading, maintenance, etc.) into manageable sectors on a hypothetical grid. Next, survey each sector by a waling tour, using file records, and talking to staff working in the area on a regular basis. Identify any possible source of air, water, or waste discharges from each sector.

2. **Mass Balance.** The first law of thermodynamics can be applied loosely to determine the inputs and outputs from a system, and therefore, to determine what may have been discharged in between. For example, if ten gallons of a solvent is used in a batch process and five gallons is disposed of as waste, approximately five gallons can be assumed to have volatilized to the air. There are some inherent problems in using the mass balance to determine wastes:

   - measurement of sufficient parameters to "get your arms around" the process is not always possible;
   - materials can significantly change form during a process (e.g., incineration, solidification); and
   - the accounting required for a large plant may be too extensive to be practical.

3. **Process-by-process.** Analyze each process (primary production, auxiliary processes, research and development, etc.) to determine where air emissions, water discharges, or waste is produced either continuously or intermittently. Knowledge of each manufacturing process and the raw materials used is vital to the completeness of this type of inventory. Estimates of the volumes of material lost to the environment at each process may be made either with measurements, engineering judgement, or by applying industry-specific emission factors.

A survey conducted by the Rubber Manufacturers' Association's environmental committee shows that:

- one-half of the firms surveyed have specific waste reduction goals;

- almost one-half of the waste stream from the industry is related to the product;
- almost one-half of the waste stream is waste such as packaging or paper; and
- less than 5 percent of the waste stream is hazardous waste and oils. (Tullys, 1992)

2.1 *SOLID, LIQUID, AND GASEOUS WASTES AND FUGITIVE EMISSIONS*

Wastes generated by the downstream petrochemical industry could be characterized by constituents found in the petroleum monomers that are similar to most manufacturing processes across the industry. Generally, off-specification solid product in downstream petrochemical industries is not reactive and may be recycled efficiently. Off-specification product such as liquid latex is also expected to be recycled. Waste materials such as acrylonitrile emissions, fugitive solvent emissions, and burned oil and grease have toxic properties that make the release of these waste materials undesirable.

In addition to petroleum-based raw materials used in the downstream petrochemical industries, there are many coatings and additives to plastics that may be potential sources of waste. Additives to plastics include metals that are used for pigment or as stabilizers. Chlorofluorocarbons are intrinsic in the molding portion of the plastics industry and are sources of potential air pollution. These chemicals are currently falling under more regulatory scrutiny, thus new compounds that are less damaging to the Earth's ozone layer are currently being phased into use.

Processing of plastics, also called polymers or resins, can involve:

- injection molding,
- extrusion,
- blow molding,
- thermoforming,
- compression molding,
- reinforced plastics molding,
- rotational molding,
- reaction injection molding, or
- casting.

At each of these operations, there is a potential for releases to the environment.

Worldwide plastics consumption is at least 125,000 million pounds. About 36 percent is processed by extruders, 32 percent by injection molding, 10 percent by blow molding, 6 percent by calenders, 5 percent in coatings, 3 percent in compression, 2 percent in powder form, and 6 percent using other processes. (Plastics Processing Data Handbook, 1990)

Common features of all plastics processing activities include:

- mixing, melting, plasticizing,
- melt transporting,
- drawing and blowing, and
- finishing (including solidification of the melt).

Most plastics manufacturing operations occur in closed vessels. However, the major sources of air pollution from this industry are:

- emissions of raw materials or monomers,
- emissions of solvents during reaction,
- emissions of sublimed solids such as phthalic anhydride in alkyd production, and
- emissions of solvents during storage and handling of thinned resins.

Throughout the downstream petrochemical industries, solid, liquid, and gaseous wastes may be released. The following sections describe some industry-specific wastes.

Synthetic Rubber Manufacturing

In the production of synthetic rubber, styrene and butadiene are monomers that are essential for the rubber production process. During the emulsion process, butadiene and styrene are polymerized continuously until approximately 60 percent of the monomers have been converted. The unreacted monomers are recovered, through vacuum flashing and steam stripping columns, for reuse in the process. Butadiene that is not used in the polymerization process is condensed and condenser tail gasses and noncondensibles pass through a butadiene adsorber/desorber unit, where more butadiene is recovered. Some noncondensibles and VOC vapors pass to the atmosphere or, at some plants, to a flare system .

Figure 2-1 represents the synthetic rubber production process, including descriptions of raw materials used in production and sources of air emissions. It is significant to note that in addition to the butadiene adsorber/desorber unit there are emissions points in the coagulation and screening, crumb rinsing, dewatering, and drying portions of the process. Waste materials are anticipated from the coagulation and screening process as sulfuric acid and brine become spent. In addition, carbon black, a significant ingredient in most rubber products, requires special waste disposal for off-specification raw materials and products containing carbon black. In portions of the process scrubbers may be added to reduce or eliminate volatile emissions, but, in other locations, such as the crumb rinsing and dewatering process emissions control may be inefficient or ineffective.

Volatile organic compounds are emitted from the manufacturing of copolymers of styrene and butadiene by the emulsion polymerization processes as described in Table 2-1. These emission factors reflect the amount of volatile emissions per unit of material processed.

Table 2-1 Emission Factors for Emulsion Styrene-butadiene Copolymer Production[a]

Process	Volatile Organic Emissions[b] (g/kg)	(lb/ton)
Emulsion Crumb		
Monomer recovery, uncontrolled[c]	2.6	5.2
Absorber vent	0.26	0.52
Blend/coagulation tank, uncontrolled[d]	0.42	0.84
Dryers[e]	2.51	5.02
Emulsion Latex		
Monomer removal		
Condenser vent[f]	8.45	16.9
Blend tanks		
Uncontrolled[f]	0.1	0.2

Source: U.S.EPA, AP-42, Section 5.20

[a] Nonmethane VOC, mainly styrene and butadiene. For emulsion crumb and emulsion latex processes only. Factors for related equipment and operations (storage, fugitives, boilers, etc.) are not included.

[b] Expressed as units per unit of copolymer produced.

[c] Average of 3 industry supplied stack tests.

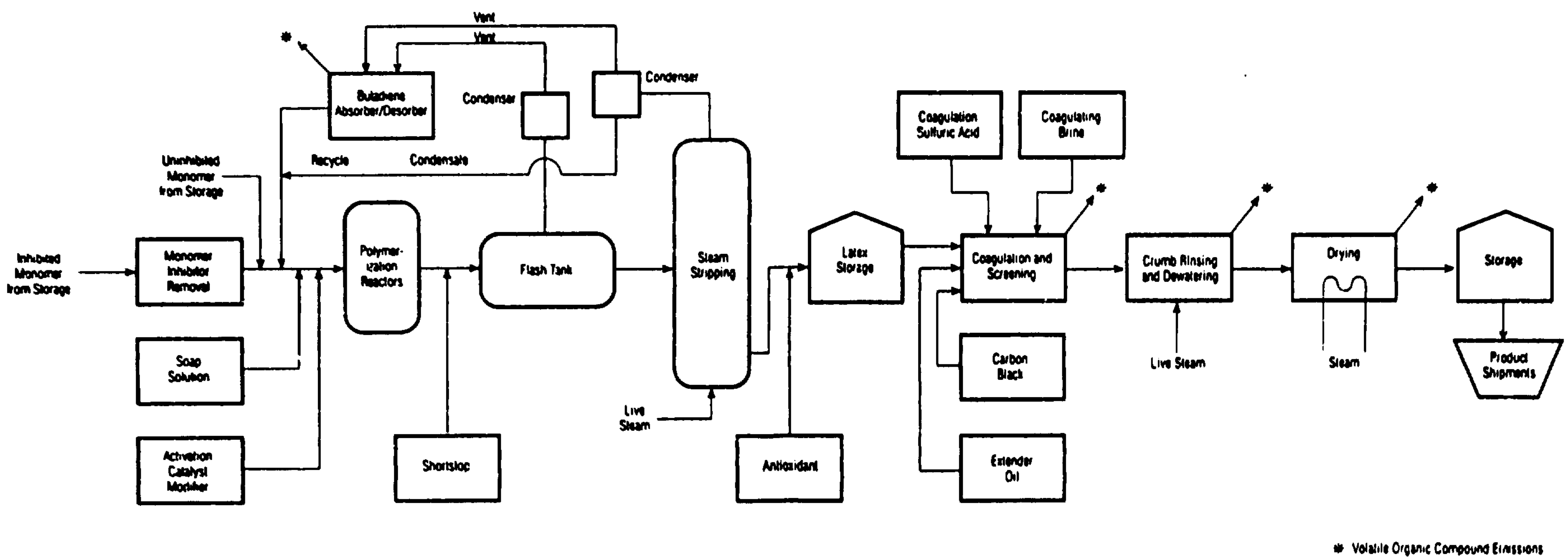
[d] Average of 1 industry stack test and 2 industry supplied emission estimates.

[e] No controls available. Average of 3 industry supplied stack tests and 1 industry estimate.

[f] U.S. EPA estimates from industry supplied data, confirmed by industry.

In the emulsion crumb process, uncontrolled noncondensed tail gases pass through either a butadiene adsorber control device that can be about 90

Figure 2-1
Typical Process for Synthetic Rubber Production



Source: U.S.E.P.A., 1986 AP 42 Figure 5.20-1 percent efficient, to the atmosphere, or to a flare. No controis are usually used for blend or coagulation tanks. Nor are controls common for emissions from dryers in the crumb process and the monomer removal portion of the latex process.

Fiberglass Manufacturing

Fiberglass is liquid polyester resin reinforced with glass fibers and extended with various inorganic filler materials such as calcium carbide, talc, mica, or small glass spheres. From fiberglass manufacturing, volatile organic compounds are emitted from fresh resin surfaces during the fabrication process and from the use of solvents (usually acetone) for cleanup of hands, tolls, molds, and spraying equipment. Cleaning solvent emissions can account for over 36 percent of the total plant volatile organic emissions (Elsherif, 1987). Fiber chopping equipment may cause air emissions of particulate matter and will create a solid waste stream.

The cross-linking agents, such as styrene and methyl methacrylate, that are used in polyester resin/fiberglass fabricating, evaporate during application and curing. The method of application affects the degree of volatilization of the agents. Table 2-2 contains information on the typical components of resins and hence the materials that have a potential to be emitted as a solid, liquid, or gas.

Table 2-2 Typical Components of Resins

To Form the Unsaturated Polyester		
Unsaturated Acids	Saturated Acids	Polyfunctional Alcohols
Maleic anhydride	Phthalic anhydride	Propylene glycol
Fumaric acid	Isophthalic acid	Ethylene glycol
	Adipic acid	Diethylene glycol
		Dipropylene glycol
		Neopentyl glycol
		Pentaerythritol

Cross-linking Agents (Monomers)
Styrene
Methyl methacrylate
Vinyl toluene
Vinyl acetate
Diallyl phthalate
Acrylamide
2-ethyl hexylacrylate

Source: U.S. EPA, AP-42, Section 4.12

Synthetic Fiber Manufacturing

The synthetic fibers industry has the potential for significant emissions releases from the generation of synthetic fibers made from polyethylene terephthalate (PET). PET polymer is one of the most widely used plastics and one that is gaining attention due to its reuse potential. PET polymer is produced from ethylene glycol and either dimethyl terephthalate (DMT) or terephthalic acid (TPA). Ethylene glycol's high water solubility could result in releases as a result of incomplete reaction to industrial pretreatment plants or water water treatment plants processing the waste water from a manufacturing facility. Polyester filament yarn and staple are manufactured either by direct melt spinning of molten PET from the polymerization equipment or by spinning reheated polymer chips.

Air pollutant emissions from polyester fiber product include polymer dust from drying operations, volatilized residual monomer, fiber lubricants, (in the form of fume or oil smoke), and the burned polymer and combustion products from cleaning the spinning equipment. Relative to the solvent spinning process, the melt spinning of polyester fibers does not generate significant amounts of volatilized monomer or polymer, so emissions control measures are typically not used in the spinning area. Finish oils that are applied in polyester fiber spinning operations are usually recovered and recirculated. Other emissions from synthetic fibers manufacturing may include:

- air pollutant emissions from the production of acrylic and modacrylic fibers include emissions of acrylonitrile (volatilized residual monomer);
- waste solvents;
- waste additives; and
- other solid wastes from fiber processing.

The major emission areas from dry spinning of acrylic and modacrylic fibers are the spinning and post-spinning areas, up through and including drying. Solvent recovery in dry-spinning of modacrylic fibers is also a major air emission point.

2.2 *REACTANT IMPURITIES, BY-PRODUCTS, AND SAMPLING, HANDLING, AND STORAGE WASTES*

Reactant impurities are becoming a larger concern in the plastic manufacturing industry. Currently, careful quality control for raw material and catalysts can control impurities from impacting the quality of a product. However, with the addition of recycled plastics as raw materials, reactant impurities are becoming a significant production consideration. Recycled plastic from the preconsumer market maintains a similar level of purity as its original monomers but post consumer recycled materials must be cleaned, dried and sorted prior to introduction into a remanufacturing process.

2.3 *SPENT MATERIALS (CATALYSTS, SOLVENTS, COOLING WATER, MAINTENANCE MATERIALS, ETC.)*

Auxiliary materials, such as catalysts and solvents may be recycled or reclaimed during a manufacturing process for a limited amount of time. Then, regardless of the effectiveness of the reclamation or recycling process the material looses its ability to modify the process in the manner for which it was intended. At this point the auxiliary material becomes a waste product. In some instances catalysts and solvents may be returned to the manufacturer for reprocessing. Solvents may also be burned for energy recovery, although contaminants from the solvent, such as metals, may concentrate in the ash resulting in ash with toxic properties.

Cooling water differs from catalysts and solvents in that generally it is used without contacting the product. Noncontact cooling waters should not have any chemical contamination although thermal pollution is expected. Contact cooling waters may be expected to have chemical contamination that is similar to the material contacted.

3.0 WASTE MINIMIZATION AND POLLUTION CONTROL

After the sources of waste are identified for the manufacturing and auxiliary processes at a facility, decisions must be made about how to reduce or control the waste streams. The decisions will be influenced by any requirements placed on the operations by local or national regulatory agencies. Product quality considerations will also play a role in what type of control will be implemented. For example, if a production process requires the use of very high quality water, the decision to implement a water recycle system should address the quality of recycled water that is able to be achieved. If extensive energy and treatment chemicals are expended to treat recycled water o the required quality, this approach may not be appropriate. On the other hand, if fresh water of high quality has been used when recycled water with a minimum of treatment is sufficient, the modification would be a good one.

This section describes some types of regulatory requirements in the United States and the United Kingdom that will drive some of the waste minimization and pollution control in downstream petrochemical industry operations. Next, three categories of waste minimization and pollution control options are discussed:

1) Short-term options that involve the installation of end-of-pipe pollution controls or source reduction that is achieved without major modifications to existing equipment or production processes.

2) Medium-term options that require a more extensive understanding of current production processes so that recycling loops may be incorporated or operational adjustments may be made to reduce the waste generated.

3) Long-term options that involve state-of-the-art solutions and a rethinking of current production and material use.

A waste management "hierarchy" begins with pollution control and proceeds to waste management, waste minimization, and then to pollution prevention. The objectives of most waste management initiatives should include provisions to move up the ladder.

3.1 REGULATORY REQUIREMENTS

In the United States, regulatory initiatives aimed at waste minimization include the Pollution Prevention Act of 1990 and the Superfund Amendments and Reauthorization Act (SARA). These regulations are examples of the move away from "end-of-pipe" thinking and toward pollution prevention at the source. The 33/50 toxics reduction program of the Pollution Prevention Act called for voluntary reduction of 17 targeted chemicals to 33 percent by 1992 and 50 percent by 1995. Pollution prevention can be accomplished through increased efficiencies in the use of raw materials, energy, water, or other resources. To achieve the greater efficiencies, changes can be made to equipment or technologies; processes or procedures; in the reformulation or redesign of products; material substitution; operational improvements; or other measures such as housekeeping, maintenance, training, or inventory control.

The hazardous air pollution title of the United States Environmental Protection Agency's Clean Air Act Amendments of 1990 focuses on categories of industry that are known to emit classes of pollutants and regulates each industry individually. Table 3-1 lists some of the industry categories and deadlines for attainment with the standards currently being developed. Controls for each category range from end-of-pipe treatments with required reduction efficiencies to maintenance procedures that eliminate emissions form such potential release points as pumps and valves.

Table 3-1 *United States Clean Air Act Industry Categories for Hazardous Air Pollutants*

Industry Category	Deadline for Attainment with Standards
acrylonitrile-butadiene-styrene production	1994
butyl rubber production	1994
epoxy resins production	1994
neoprene production	1994
polybutadiene rubber production	1994
acetal resins production	1997
butadiene dimer production	1997
phenolic resins production	1997
polyester resins production	1997
polyvinyl acetate emulsions production	1997
rubber chemicals manufacturing	1997

In the United Kingdom, the Environmental Protection Act affects most rubber processing companies. The requirements apply to factories that mill or blend natural or synthetic rubber that involves carbon black, or further processing. Emissions limits for rubber factories are 50 milligrams per cubic meter (mg/m^3) for particulates, 10 mg/m^3 for carbon black and 0.1 mg/m^3 for isocyanates. (Rubber, 1992)

According to Ken Straugham, medial director for the British Rubber Manufacturer's Association, the United Kingdom's Environmental Protection Act of 1990 will impose high capital cost burdens on the rubber industry. (White, 1992) Rubber processes that fall under the act include

- combustion of rubber waste and of rubber tires, thermal input 0.4 to 3 megawatts,
- processes using 5 tons or more of organic solvent in any 12 months with a coating process, and
- coating manufacturing processes using 100 tons or more of organic solvent a year.

The definition of a rubber process is one that involves mixing, milling, or blending of a natural rubber or synthetic elastomer if carbon black is used. Latex processing is not covered by the rubber process regulations. In the rubber industry, some of the most significant effects of the United Kingdom's Environmental Protection Act will be in ancillary operations not central to the process; for example, use of organic solvents and isocyantates in adhesives.

Table 3-2 describes the emissions limits and monitoring requirements for the United Kingdom's Environmental Protection Act.

Table 3-2 Requirements for Rubber Industry Under the United Kingdom's Environmental Protection Act

Emissions Limits for Air

Type of Emissions	Limit (mg/m^3)
Total particulate matter from storage, handling, or mixing of carbon black	10
Total particulate matter from sources/operations other than those listed above	50
Isocyanates (as total NCO group) excluding particulate matter	0.1
Volatile organic compounds (as total carbon excluding particulate matter)	0.1
Carbon monoxide (from incinerators)	100
Nitrogen oxides, measured as NO_2 (from incinerators)	100

Monitoring Requirements

Flow Rate	Requirements
>300 m^3/min	Continuous quantitative monitoring
50 m^3/min – 300 m^3/min	Indicative monitoring with failure clause
< 50 m^3/min	No monitoring

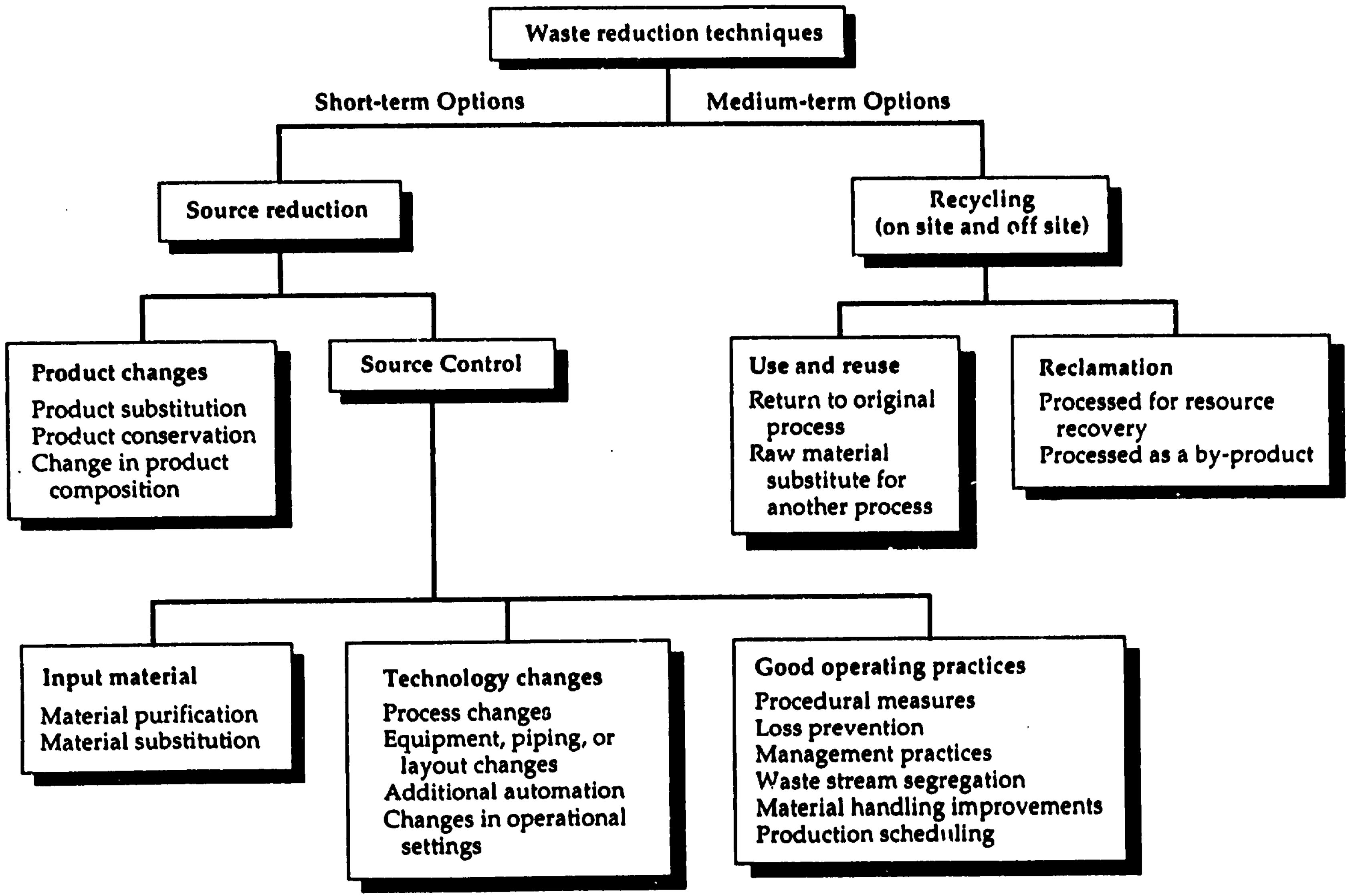
3.2 SHORT-TERM OPTIONS: SOURCE REDUCTION AND END-OF-PIPE TREATMENT

A summary of waste reduction techniques are shown in Figure 3-1. Source reduction, shown on the left side of Figure 3-1, can be thought of as either changes to the product and its components during manufacturing or as source control where input materials can be changed, technological changes can be made, or operational practices can be modified to reduce waste. Source reduction can also be thought of as a three-tiered approach:

1) get the "low-hanging fruit" that is easily identified, able to be attained quickly, and does not cost much (e.g., good housekeeping measures, minor equipment adjustments, etc.);

2) identify process changes -- these will require a one to five year lead time and may require more capital investment; and

Figure 3-1 Waste Reduction Approaches



3) back to basics measures -- these will require more than five years lead time, more capital, and will involve such changes as new raw materials or process redesign.

In general, the cost goes up with each of these tiers and the risk of failure increases as well. Many argue that the best waste management approach is never to create wastes and therefore not need to tools to manage the problems associated with wastes. However, source reduction will not always be feasible.

It may be difficult to find source reduction options that have the degree of efficiency of many end-of-pipe treatments. Often, when a facility is faced with short-term requirements, it is driven to end-of-pipe methods. These changes may include changes to processes that are easily made, that require little capital input and result in quickly recognizable reductions in waste. Often, these immediate control options result in a cost savings for raw materials or waste disposal.

In addition to process changes and material substitution, add-on controls can be used to decrease vapor emissions from styrene resin, though low exhaust VOC concentrations and the potential for contamination of adsorbent material makes control difficult. Most plants use forced ventilation to decrease exposure to styrene vapors, but vent vapors to the atmosphere, not to a control device. Incineration has been used for control of these volatiles, and, to a lesser extent carbon adsorption, absorption, and condensation.

Table 3-4 describes the air emissions from plastics manufacturing operations before controls, in terms of pounds of emissions per ton of material processed.

Most air pollution control equipment for plastics manufacturing operations is integrated with the production equipment such as:

- floating roof tanks,
- volatile recovery systems (adsorbers or condensers),
- purge lines that vent to flares, and
- recovery systems on vacuum exhaust lines.

Table 3-4 Emission Factors for Plastics Manufacturing without Controls[a]

Type of plastic	Particulate (lb/ton)	Particulate (kg/MT)	Gases (lb/ton)	Gases (kg/MT)
Polyvinyl chloride	35[b]	17.5[b]	17[c]	8.5[c]
Polypropylene	3	1.5	0.7[d]	0.35[d]
General	5 to 10	2.5 to 5	–	–

Source: U.S. EPA, AP-42, Section 5.13

[a] From Shreve, 1967 and Larsen, 1962.

[b] Usually controlled with a fabric filter efficiency of 98 to 99 percent.

[c] As vinyl chloride.

[d] As propylene.

In the United Kingdom, the Environmental Protection Act of 1990 puts stringent limits on vapor and particulate matter emissions from rubber mixing and milling operations. Dust control equipment and filters are essential to meet the Environmental Protection Act limits.

Process equipment improvements are needed in rubber mixing, not just add-on pollution control. Dust seals, filters, and enclosed pneumatic conveying systems for materials handling are some requirements.

3.3 *MEDIUM-TERM OPTIONS: PROVEN TECHNOLOGIES, RECYCLING, AND OPERATIONAL ADJUSTMENTS*

Recycling alternatives are shown on the right side of Figure 3-1. These options may not be available to all phases of production. For example, material substitution is more likely to be used in periphery operations than in critical production steps. It is more likely that materials will be substituted, for example, in degreasing or maintenance activities, than in chemical synthesis and production. This level of pollution control requires more time to implement (usually one to five years), thus it is not well suited for regulatory compliance. This type of project generally involves investment into known technology for the reduction of pollution and frequently capital investments are greater than long term cost reductions.

Emissions from cleanup solvents can be controlled through good housekeeping (e.g., container covers), reclamation of spent solvents, and substitution of solvents with volatile components with water-based solvents.

Table 3-3 lists a range of waste reduction approaches that have been taken by petrochemical industries, both in primary production and auxiliary processes.

The most cost-effective method for reducing solvent volatile organic compound emissions from both wet and dry spinning processes is a solvent recovery system. In wet spinning processes, distillation is used to recover and recycle solvent from the solvent/water stream that circulated through the spinning washing and drawing operations. In dry spinning processes, control techniques include scrubbers, condensers, and carbon adsorption. Scrubbers and condensers are used to recover solvent emissions from storage tank vents and from mixing and filtering operations. Distillation columns are also used in dry spinning processes to recover solvent from the condenser, scrubber, and wash water.

Currently, there are approximately 12 cement kiln facilities burning scrap tires across the United States, thereby recycling scrap tiers into reusable alternative fuel. According to the United States Environmental Protection Agency, cement kilns appear to be very suitable for scrap tire disposal because the furnaces operate at very high temperatures with long residence times. Tires have a high fuel value. This practice began in 1972 and was extensively tested as a waste disposal method, described as "best demonstrated available technology" (BDAT) for scrap tire disposal. The conversion of cement kilns from burning coal to burning tires requires a small capital investment.

Bridgestone/Firestone recently announced that United States and Canadian patents owned by its parent company, Bridgestone Corporation, and dealing with the use of whole scrap tiers for cement kiln fuel will be licensed to interested companies without charge. Use of whole scrap tires during the patented process in cement kilns offers better economics than using tire derived fuel (TDF) from shredded scrap tires, so the availability of the patent should expand the use of scrap tires in cement kilns. The Bridgestone/Firestone patents claim an effective method for using whole or cut scrap tires in a rotary cement kiln by feeding them at a position where the temperature of the exhaust gases is 600-1400 °C in an amount not to exceed 60 percent of the total fuel requirements. (Holman, 1992)

Doug Pearson, managing director of Watts Industrial Tyres says that "everywhere, the United Kingdom, the United States, Europe, people want quality, but also pricing is so acute that scrap must be totally minimized. We must get it right the first time." (White, 1992)

At Swedish compounder and processor Forsheda, scrap rates are "a lot less than 1 percent," according to Bengt Andersson, technical project

Table 3-3 Example Waste Reduction Approaches

	Production/process	Waste/emissions	Reduction volume	Percent	Method/changes
Air Products & Chemicals	Spray painting	Acetone	na	94%	Material substitution
	Compression systems	Lubricating oil	2100 gal	70	Treatment/reuse
	Chemical cleaning	Spent solution	81,000 lb	69	Operational
Allied-Signal	Clean room	Chlorofluorocarbon	26,000 lb	na	Material substitution
Dow Chemical	Polycarbonate	Methylene chloride	360,000 lb	na	Recovery/recycling
	Chlorine cell diaphragms	Asbestos	3.3 million lb	na	Product design
Du Pont	Packaging films	Plastic films	2.7 million lb	87	Recycling/resale
	Automotive finishes	Methyl amyl ketone/ methyl isobutyl ketone	1 million lb	na	Recycling/reuse
		Volatile organics	na	68	Process changes
	Acrylonitrile	Ammonium sulfate	70 million lb	70	Process changes
Eastman Chemical	Polymer production Organics manufacture	Methyl cyclohexane methanol	3 million lb	na	Recovery/reuse
		Isopropyl alcohol	na	95	Recovery
	Acetic/butyric acids	Acetic acid	250,000 lb	na	Recovery
	Organic wastestream	Methyl isobutyl ketone	1 million lb	90	Recovery
FMC	Hydrogen peroxide	Methanol	>200,000 gal.	90	Recovery/reuse
Monsanto	p-Dichlorobenzene	Air emissions	1 million lb	na	Recovery/recycling
	Polyphenol	Solid waste		na	Burned for energy
Union Carbide	Olefins	Benzene[a]	>100,000 lb	40-50	Process change/recycling
	Vinyl resins	Acetone	2 million lb	na	Operational

[a] Also reduced methanol use by 3 million lb. na = not available.

manager. Forsheda has a scrap minimizing policy and their mixing facilities are designed to eliminate dust. The major environmental problem in rubber compounding is the use of carbon black, with its ability to spread and contaminate every surface at a factory. Solutions to this problem may include:

- automated materials handling
- better equipment seals
- good housekeeping measures

Forsheda has a central vacuum system for cleaning plus a waste disposal system where waste packaging can be thoroughly disposed.

Dust suppression in rubber mixing can be achieved by:

- storing materials in bins,
- employing seals on handling equipment,
- using dust-free powers that are polymer bound or wetted (if possible).

3.4 *LONG-TERM OPTIONS: INNOVATIVE TECHNOLOGIES*

Long-term options for pollution control may be characterized as top-down approaches. Long-term approaches to pollution reduction may require more than five years. This approach involves the research of the basic process design and chemistry in a effort to "rethink" the production approach. Long term control may involve the substitution of raw materials, process redesign, or product changes. These modifications may require redesign of existing plants or the construction of new plants.

4.0 *ECONOMICS OF WASTE MINIMIZATION AND POLLUTION CONTROL*

It can be difficult to quantify costs of some environmental impacts. For example, a product's cost to ecological integrity versus human health benefits is not a straightforward calculation. A variety of techniques exist for attempting to determine a price that reflects the utility of nonmarketed goods, services, and amenities. All such techniques rest on questionable assumptions. Nevertheless, they provide a means to compare apples and oranges, that is, marketed versus nonmarketed goods.

The "costs" of environmental disruption may be viewed as the loss of the free benefits of nature in the undisrupted state. Figure 4-1 illustrates a range of such benefits. Some of nature's benefits have market prices, namely, such goods as timber, certain species of wildlife, soil and minerals, as seen on the left side of Figure 4-1. By contrast, the functions of ecosystems, the dynamics of exchange of mass and energy, are nature's free services (right side of Figure 4-1). These are typically not sold in the marketplace and have traditionally been totally neglected in cost-benefit analyses.

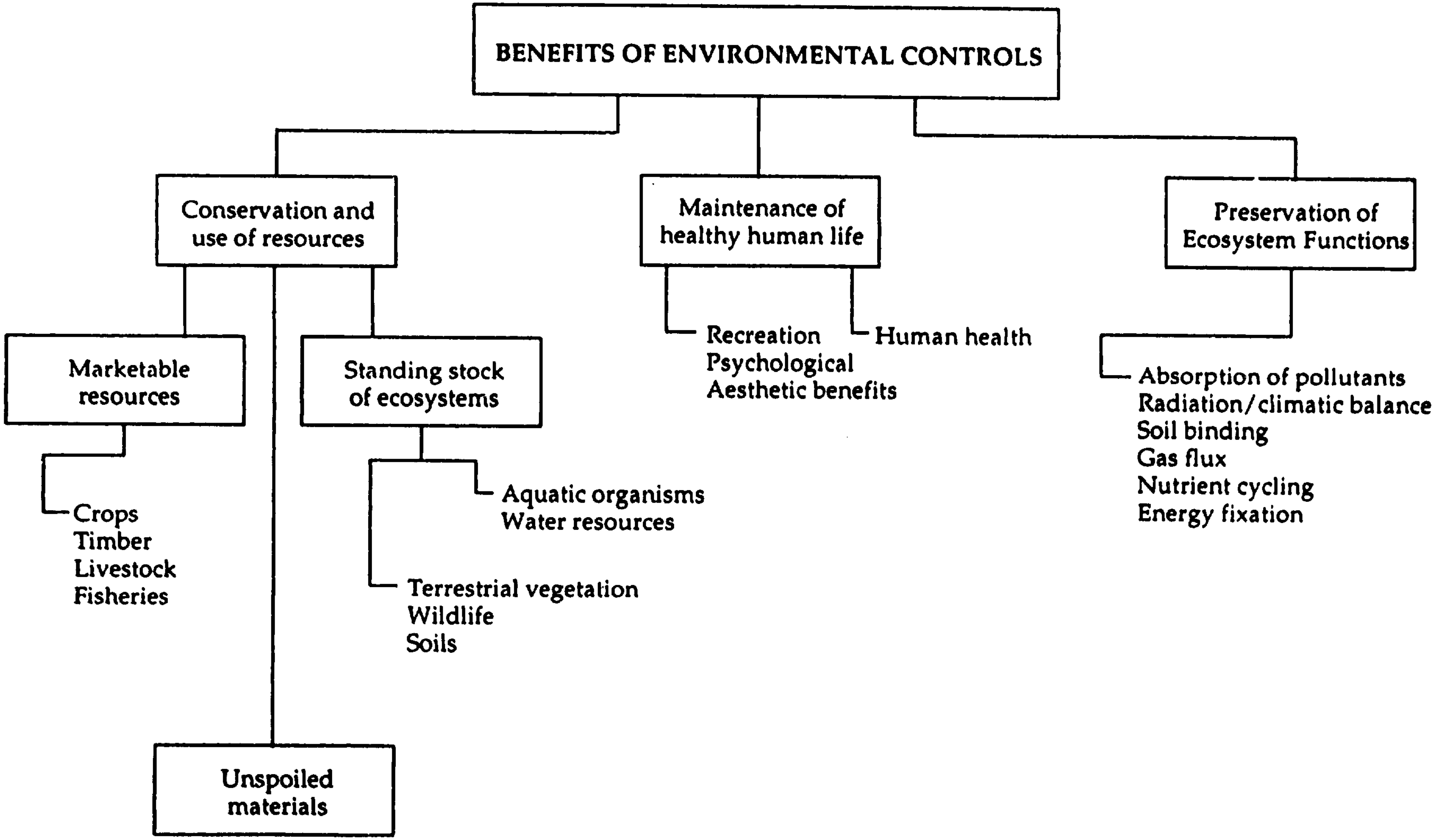
The benefits of nature to people can be categorized as direct and indirect. The direct benefits usually arise from the enjoyment or harvest of ecosystem features (e.g., food medicine, fiber, shade, recreation from plants and animals), the indirect benefits more typically form ecosystem functions (e.g., gas exchange, radiation balance, pest regulation). More typically in economic evaluations we are concerned with the benefits of preserving nature in the unimpacted state as opposed to the benefits of resource development. From this perspective, the benefits of pollution control arise from the lessened damages to the free goods and services of nature (direct benefits) and from the reduced costs of repairing damages (indirect benefits).

Some of the general problems encountered in evaluating nonmarket goods in economic terms include the following.

1) Different methods (e.g., damage costs vs. repair costs) result in different economic estimates for the same resource; the degree of incompleteness of each estimate is usually unknown, making it difficult to choose between them.

2) Because nature's goods and services are free to begin with, their economical value not fully appreciated, many shadow-pricing methods underestimate the true value of the resource to people.

Figure 4-1 Three Major Categories of Benefit from Reducing Environmental Damage



Adapted from Westman, 1985

3) Because people value money differently, a price fails to reflect the differing weights attached to the evaluation unit (money).

4) Because people value natural resources differently but prices reflect aggregated or average social utilities, the differing values attached to a resource by different publics are not separately indicated.

5) Some of nature's gods and services are not readily evaluated in economic terms by existing methods either because they are too complex and incompletely known (e.g., global climate) or because they are not considered exchangeable for money (e.g., human life); these items are often excluded from economic analyses, making these analyses incomplete.
(Westman, 1985)

A recent study by the New York City-based environmental research group Inform describes efforts at 27 chemical manufacturing plants. More than 180 source reduction activities were tracked in the study. These activities generally were found to provide both environmental benefits, through reducing a total of 129 million pounds of waste per year, and economic benefits to the companies involved. The majority of source reduction activities required relatively minor implementation through refinements or alterations in processes, equipment changes or additions, or through making operational changes. Less than 15 percent involved product changes or chemical substitutions. More than half of the projects reported greater than 90 percent reduction in waste production with the average being 71 percent. Implementation times were not long, with about tow thirds of the projects taking less than six months to complete from research and development to implementation. In a few cases, no capital expenditures were made for source reduction activities and in just about half of the cases less than U.S.$100,000 was spent. Between U.S.$45,000 to U.S.$1 million in savings were achieved in about half of the projects in the study. And, when reported, more than two thirds of the firms recouped their expenditures in six months or less. (Thayer, 1992)

At the Union Carbide Seadrift plant, process changes to reduce benzene releases and methanol use cost the company $8 million to implement. Although the reductions were dramatic, only about $250,000 per year are saved as a result. (Thayer, 1992) These are not good payback scales, but economic benefits alone are not the motivator for the project. This plant is also serving as a test case for the Chemical Manufacturers' Association mandated Responsible Care provisions. At the Seadrift plant a community group of neighbors to the plant has been formed to explain past incidences and to keep the community informed of plant operations. These guidelines are enforced by Chemical Manufacturers' Association and failure to comply could result in the expulsion of a member company.

5.0 *TOOLS FOR ENVIRONMENTAL CONSERVATION*

5.1 *POST-CONSUMER WASTE MANAGEMENT*

Post consumer waste management is a growing field world wide. Currently, the majority of the plastics and synthetic rubbers produced are being included in the municipal waste stream and are not recycled. In western Europe, a significant portion of the municipal solid waste (including plastics and rubber) produced is landfilled, the next most utilized waste disposal method is incineration and finally, recycling methods such as incineration for energy or recycling of monomers play the least significant role in waste disposal. Other countries, such as Japan, have more aggressive recycling programs currently in place, as can be seen in Table 5-1.

Table 5-1 ***Comparison of Plastics Waste Handling (1990)***

	Japan	United States	Europe
Source	11	24	27
Total plastics production, MMTPY	4.9 (total)[a]	11.8 (MSW only)[b]	12.5 (total)
Plastics waste stream, MMTPY	44 (total)[a]	49 (MSW only)	46 (total)
Plastics waste stream, percent of plastics production	12	3 (MSW only)	8
Disposition[c]			
Recycled, %	12	3 (MSW only)	8
Landfill, %	23	80 (MSW only)	64
Incinerate, %	65[d]	17 (MSW only)	29
Refuse-derived fuel, %	negligible	1.5	NA[e]
Total, %	100	100	100

Source: Eller, 1992 from Charles River Associates, 1991.
[a] Total = MSW + industrial waste
[b] Excludes industrial waste
[c] Rounded off; may total over 100%
[d] 25% of incinerated plastic waste in Japan is converted to electrical power
[e] Not available
MMTPY = million tons per year
MSW = municipal solid waste

It is significant to note that Japan and Europe included post consumer uses such as industrial scrap plastics such as thin film wrap and shipping materials while the figures presented for the United States represent only post consumer municipal solid waste.

Increased recycling efforts are being made world wide in industrialized nations where landfill space is at a premium. In countries such as the United States and Western Europe there are currently ongoing efforts to promulgate strict regulation regarding the amount of plastics that must be recycled each year. The European Community is currently striving for a rate of recycling that is equal to 90 percent of the waste plastic produced in the Community. The impact of this will be amplified because in the European Community any plastic wrapping material that is shipped between countries is considered post industrial waste.

Intermediary Production of Resins

Post consumer waste plastics are an integral part of value added products. These products contain various quantities of resins that were obtained through the post consumer market. These post consumer resins have been washed, sorted and pelletized prior to addition into product production.

Monomer Reclamation

Monomer reclamation or tertiary recycling involves the reduction of the plastic to its base construction which allows for the assembly of new polymers or the use of the reduced plastic as a petrochemical feedstock. This technology is beneficial because it can be used for reclamation of waste plastics that can not currently be recycled via resin reclamation (such as medical wastes, auto-shredder wastes and blended or compound wastes). In addition, thermal depolymerization does not require cleaning or decontamination and is able to act efficiently on mixed plastic wastes.

Tertiary recycling involves the chemical unzipping (hydrolysis) or the thermal cracking (pyrolysis) of polymer chains. The monomers or petrochemicals that are recovered as a result of this cracking are reported to be indistinguishable from the virgin materials (Randall, *et al*, 1992). Their are two basic types of depolymerization, those that "unzip" a polymer to their immediate precursors such that they can be remade into the same plastic via a reversible reaction and those that reduce the plastic to its most basic monomers that are indistinguishable from virgin materials. The second method is used for those plastics that are formed by an irreversible process.

Reversible reactions include chemical depolymerization which has been used in the polyester manufacturing industry for many years where PET from industrial plant scraps were broken down to monomers. This technology is currently being expanded to included the post consumer waste PET produced by the use of soft drinks. The second reversible reaction is thermal depolymerization which is best suited to reclamation of specific polymers such as polystyrene. In this process the monomers are isolated and purified before being used to make new plastics. This technology is currently in used in India where it is being used to reclaim polymethylmethacrylate (Randall, *et al*, 1992).

Pyrolitic conversion of materials encompasses the second method of monomer recovery. Their are two basic types of conversion: liquefaction and gasification. Pyrolitic liquifaction is similar to the thermal depolymerization except that the product is the liquid precursors instead of the monomers. This method is advantageous because it can treat those polymers that can be treated by thermal depolymerization in addition to those resins that can not be reduced via the thermal method, and, separation of plastics or cleaning of the materials is unnecessary because all materials can be pyrolyzed in the course of the process. In addition, the resultant product from this process is a liquid which most refining or manufacturing facilities are equipped to handle. The second technology, pyrolitic gasification produces gas from the petrochemical feedstock. This process, which includes steam cracking and syngas production, often employs the use of catalysts or a feed material such as naphtha. Researchers in the field feel that this may be one of the most efficient means of materials reclamations from plastics due to the flexibility of the feed material, the ability to accept soiled or contaminated materials, and the relative simplicity of the process (Randall, *et al*, 1992).

Energy Recovery

Energy recovery from waste plastics and tires may be achieved by incineration of the waste feedstock for electricity or steam or through depolymerization discussed previously. Incineration of waste for energy recovery currently represents a small portion of the incineration that takes place. This method of energy recovery is expected to increase as the regulatory required recycling increases. The European Community is currently negotiating an integrated waste management program for its member countries that includes the use of energy recovering incineration as a means of recycling, however, the percentage of waste plastic material that may be burned for energy recovery as part of their proposed 90% plastics recycling will be limited. Depolymerized materials may also be burned in the same manner as gasoline or fuel oils after the material has been refined in the same manner as crude oil. Burning of fuel oils is a wide spread method of energy generation and therefore, no adaptation of existing equipment is necessary to recoup energy from depolymerized waste plastics. In addition, pilot studies of pyrolyzation indicate that heavy oils can be produced profitably from plastics, thus this mode of energy recovery could be a viable method of material reuse (Randall, *et al*, 1992).

5.2 *AUDITING, WASTE REDUCTION, ENVIRONMENTAL COMPLIANCE*

In the United States, the Chemical Manufacturers' Association has developed a code of conduct known as Responsible Care. This code outlines six principles that each member company has pledged to uphold; these include:

- Community awareness and emergency response
- Pollution Prevention
- Process Safety
- Distribution
- Employee Health and Safety
- Product Stewardship

This initiative has established guidelines, that are not mandated by the federal government, which present a code of conduct for all of Chemical Manufacturers' Association's member companies. Two facets of this code (pollution prevention and process safety) employ audits as a means of identifying the strengths and weaknesses of each plant or process. Each has different requirements for the audit, thus pollution prevention will be assessed first.

Pollution prevention may be undertaken to comply with regulatory guidance or private industry guidance, however reduction or prevention of waste can also result in reduced expenditures. The Chemical Manufacturers' Association's pollution prevention program requires that companies inventory wastes that are released to all media, solicit input from employees and the public with regard to plans for continual reduction, evaluate reducing wastes prior to considering recycling or treatment programs, include the previous objectives in research and development for new or modified processes, and maintain a program promoting the development and maintenance of other pollution prevention programs. Studies have shown that in the chemical industry this approach has reduced the volume of waste by amounts around 10 million pounds per year. In addition, the capital expenditure for these types of reductions were, in many instances small, and further expenditures were achieved because, in some instances, the cost of the reduced waste production resulted in reduced operating costs (up to one million dollars per year) (Ember, 1992). While this type of savings is not consistent, some industrial facilities are finding that pollution prevention is beneficial to their processes.

Process safety could also be undertaken to meet regulatory or private industrial guidance. The goal of this discipline is to prevent fires, explosions or releases of material as a result of an accident. Process safety incorporates, but exceeds the goal to protect workers and the community from hazardous releases. It provides a management tool for prioritizing capital expenditures to minimize the risks associated with manufacturing processes, development of tiers of preparedness to prevent escalation of an event, and to train employees and emergency responders to safe work habits and potential hazards within a facility. Audits are an integral part of this process. Issues identified in audits may be proposed for corrective actions and may be added to scheduled maintenance programs.

5.3 *ENVIRONMENTAL IMPACT ASSESSMENT*

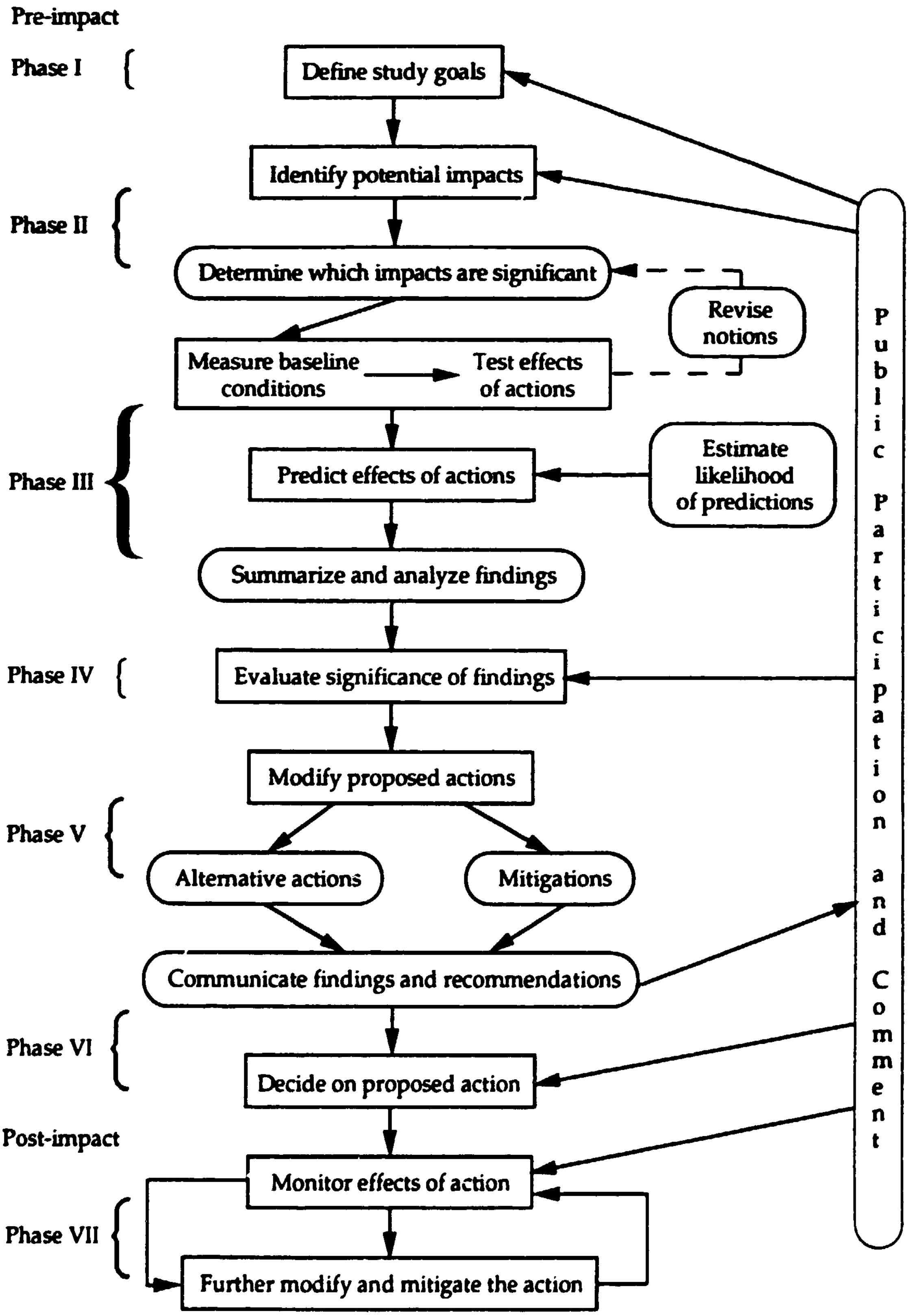
An accurate prediction of impacts to a site cannot be made without a knowledge of the other proposed projects for the area and the intensity of direct and indirect stresses they will impose on the site. Thus the marine life in a bay may be able to resist severe impact from an oil tanker terminal or an oil refinery alone, but not the combined impacts of the two. For an accurate prediction of cumulative impacts to be made, impact analysis must be able to refer to some plan for the future development of the region. The plans in turn usually derive from a set of policies for regional development and national goals and values. To speak to the combined effects of independent proposals for a region, impact assessment is dependent on regional planning. To be comprehensive and systematic, planning should proceed from the level of national goals to regional and local considerations.

A possible sequence for conducting an impact assessment is illustrated in Figure 5-1. Questions that may guide the formulation of the pre-impact phases of an impact study are provided below, as asked by Westman, 1985.

Phase I: *Defining Study Goals*

1. What information is needed, and how precise must it be for
    a. The proponent to minimize environmental impact?
    b. The government agency to reach a decision on approving the project?
    c. Concerned groups to know how thy will be affected?
2. What resources are needed for the study? What resources are available?
    a. What expertise is needed? Available?
    b. How much time is needed for baseline and experimental studies? How much time remains before the project is supposed to begin?
    c. How much money is needed to conduct the proposed studies? How much is available?

Figure 5-1 Phases of Impact Assessment



Adapted from Westman, 1985

Phase II: Identifying Potential Impacts

1. What are the boundaries of potential impacts?
   a. Area affected.
   b. Organisms or ecological functions affected.
   c. Duration of the project.
   d. Interval before the effects occur.
   e. Duration of effects with and without mitigation.
2. What is the range of potential impacts?
   a. Major direct actions.
   b. Major ecological components (air, water, land, biota, structures) affected.
   c. Major ecological processes affected.
   d. Secondary or higher-order interactions.
   e. Indirect effects triggered at a future time or different place.
   f. Other actions (past, present, reasonable foreseeable future) that may add to the present action, causing cumulative effects.
3. Which potential impacts are most significant? Which effects will
   a. Violate existing laws, plans, or policies?
   b. Cause major adverse effects of species population numbers?
   c. Cause major disruption to ecosystem processes, affecting species significantly?
   d. Cause health risks, economic losses, or significant social disruption to people?

Phase III: Measuring Baseline Conditions and Predicting Significant Impacts

1. Baseline Conditions: What are the significant features of the ecosystem presently?
   a. What is the current pattern of fluctuation in population sizes for important species (measured over sufficient time to characterize the range of variation)?
   b. Which species are playing a dominant or critical role in maintaining ecosystem processes? What is their abundance, distribution, and functional behavior?
   c. What is the condition (quality, quantity, dynamics) of physical resources of the ecosystem?

d. What are the major pathways of interaction between ecological components?

e. What sources of stress from natural or human-induced sources already exist (fire, air pollution, grazing, etc.)? With what intensity and periodicity do these stresses occur?

2. Predictions: What will be the major effects of the proposed action? What is known from each of the following?

a. Case Studies: Extrapolation of effect from similar instances of disruption to the same or similar ecosystems elsewhere.

b. Modeling: Predictions from conceptual or quantitative models of ecosystems interaction.

c. Bioassay and Microcosm Studies: The effects of simulated disturbances on ecosystem components under controlled conditions.

d. Field Perturbation Studies: Response of a portion of the proposed project area to experimental disturbance.

e. Theoretical Considerations: Predictions of effect from current ecological theory.

3. Estimation of Likelihood:

a. What is the probability of occurrence of the predicted events?

b. How precisely can the magnitude and likelihood of impacts be estimated?

4. Summarizing and Analyzing Findings:

a. How can findings be summarized in tables, graphs, or indexes so that key finding emerge?

b. What is the ecological interpretation of the findings?

Phase IV: Evaluating Significance of Findings

1. How are the effects distributed among affected groups?

a. What is the nature and magnitude of impact on each affected group?

b. What weight shall be given to the concerns of each group?

c. What weight does each group give to the significance of predicted effects?

2. How well are goals achieved by the proposal?

a. Proponent's goals?

b. Governmental goals and policies?

c. Goals of affected groups?

3. What is the overall social significance of the predicted ecological effects?

   a. How can effects be expressed in terms that allow meaningful comparison with other social goods, services, and values?

   b. If monetary values are placed on normally unpriced goods and services, what features are inadequately evaluated by this procedure?

Phase V: Considering Alternative to the Proposed Action

1. What alternatives to the proposed action exist?

   a. What would be the effect of not proceeding with the project?

   b. What would be the effect of achieving ultimate project goals by an entirely different means (e.g., maintaining electrical service to a growing population by conserving energy rather than building a new power plant)?

   c. What alternative designs could achieve project goals?

2. What steps could be taken to mitigate adverse environmental effects of the proposed project?

   a. Could parts of the proposal be reduced or eliminated?

   b. Could expected damage be repaired or rehabilitated?

   c. Could ongoing management procedures be instituted to reduce damage?

   d. Could affected components be replaced or owners compensated?

   e. Could project design be modified to reduce effects?

   f. Could effects be monitored, and provision made for future mitigation of project effects when the exact nature and extent of effects are better known?

5.4 LIFE-CYCLE ANALYSIS

The environmental impact of all phases of industrial activity, from raw materials acquisition and research and development, to the final disposition of a product and its packaging, has a far-reaching effect on air and water quality and on public health. As a result, industry, environmental groups, and governments are attempting to identify a systematic means of evaluating and minimizing the environmental impact of products and processes. One of the more promising systematic approaches for identifying and evaluating opportunities to improve the environmental performance of industrial activity is termed *life cycle analysis*. Life cycle analysis provides an analytical framework for investigating the entire range of environmental impacts (e.g., air emissions, waste water, solid and hazardous waste, renewable resources, and energy use.

Life cycle analysis may reveal solutions to productivity questions that may not seem obvious. Three major considerations that are incorporated into developing a cost based on life cycle are:

- manufacturing,
- owner operations, and
- final disposal.

Manufacturing costs cover the expenditures required to produce a piece of equipment, or in the case of a cost comparison, to manufacture several equivalent pieces. Owner operation costs include the operation costs for the end user (such as gasoline in an automobile). And, final disposal costs are the costs of disposing of the object once its useful life has passed. This cost may include landfilling or recycling.

One life cycle study found that when the total life costs for manufacturing automobile body panels were calculated plastics were an economical production material. Based on this study's assessment, the amount of waste resulting from the manufacturing of roof panel was less than both steel and aluminum parent material, and even with the added total-life cost of landfilling the plastic automobile part, plastic construction was a very reasonable alternative to the common metal body parts.

Life cycle considerations can be seen to cover all organizational areas of an operation, including materials management, packaging and transportation, and sales and marketing. It can be organized and implemented by a company on a line-by-line basis, on a product or class of products basis, by corporate offices, or at each facility.

Product Stewardship is one of the six codes of management practice championed by the Chemical Manufacturers' Association, the 182-member organization representing the interests of chemical producers. Product Stewardship asks manufacturers to assume responsibility for the environmental, health, and safety consequences of products throughout their life cycles, from initial design to final disposal. During design, manufacturers must consider the environmental effects, including energy costs and pollution, of using certain raw materials. Companies also must assume responsibility for environmental and human costs of the disposal of products. In its final form, Product Stewardship contains 12 management practices:

- senior management leadership;
- accountability and performance measurement for implementing Product Stewardship company wide;
- resource commitments;
- developing and maintaining information on health, safety, and environmental hazards relevant to each product;
- characterizing product risk;
- establishing risk management systems;
- systems for product and process design and improvement;
- employee education and feedback on product use;
- selecting, educating, and evaluation contract manufactures;
- establishing requirements for suppliers;
- selecting, educating, and evaluating distributors; and
- obligations to customers and other direct product receivers, as well as obligations customers owe to suppliers.

Bill Haaf, environmental issues manager for corporate environmental affairs at E.I du Pont de Nemours and Company, Inc. in Wilmington, Delaware, U.S.A. offers an example of the life cycle concept. In order to do a life cycle analysis of a product such as nylon, you need to go all the way back to coal and petrochemical feedstocks and ask, "How much of that did you use to get feedstock out of the ground?" Then, at the plant site, the questions are, "How much energy does it take to made butadiene and other components of nylon production? What are the air emissions? What are the water emissions? What are the solid wastes?"

After the products are moved to a site where nylon is made, DuPont must ask "What are the air emissions? What are the water emissions? What is the energy use?" Now, the nylon goes to somebody who spins it into carpet, and they should ask "What are their air emissions? What are their water emissions?"

Refusing to sell a product is a logical extension of Product Stewardship. Although a rare phenomenon to date, this could occur if a manufacturer expects that a customer would use a product in an unsafe manner. However, it is not always clear to the seller how the product is being handled. A potentially more contentious problem with Product Stewardship is whether corporate liability is increased when others in the product's life cycle do not practice safe management or disposal.

The main center of plastics research and development in the Netherlands is the TNO Plastics and Rubber Institute in Delft, with about 150 employees. The environmental department of the organization has extensive experience in preparing life cycle analysis and 5-6 people working on such studies. TNO is involved in several recycling technology projects. One is looking at eliminating the regranulating stage of the recycling process to make it more cost effective. The idea is to integrate the homogenizing/extrusion phase of the recycling process with the processing of the plastic into a semi-finished or finished product. (Dutch Research Institute, 1993)

5.5 *RISK MANAGEMENT*

Risk management can be practiced throughout the downstream petrochemical industries by management as well as workers throughout the plant. Risk management can result in several benefits including:

- operating safely in-house and minimizing accidents; and
- minimizing accidental releases of pollutants to the environment through planning.

Management can avoid bad acquisitions or purchases by evaluating the risks at a facility prior to investing capitol or subjecting any workers to unwarrented risk.

5.6 *LAND-USE PLANNING*

Land-use planning plays an important role for industry in deciding how to best use company property and where to expand operations or conserve natural resources. Operations common to downstream petrochemical industry facilities that require special land-use planning considerations include:

- landfills — should be located above the water table, lined, and vented to the atmosphere or to a flare;
- liquid storage lagoons — should be lined, located above the water table, and access should be limited;

- tank farms — catch basins, with adequate capacity, should surround each tank or each group of tanks storing compatible materials;
- waste water treatment — water should be treated sufficiently for the receiving body of water, land-application of sludge should only be practiced after extensive analysis of the sludge.

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