CHAPTER IV
ENERGY AND ENVIRONMENTAL ASSESSMENT FOR POLYAMIDE FIBER PRODUCTION

ABSTRACT: Life cycle assessment is a new method used for evaluate the environmental burden from products. In this study, environmental performance of two types of polyamide chip (T-100 and T-200) used for polyamide fiber production in Thailand, was determined. Simapro 5.1 software was used to analyze and estimate the environmental impact of the two products. The methods used to evaluate the data were Eco-indicator 95 and 99. A comparison between polyamide chips type T-100 and T-200, functional unit was one ton of the chip, showed that T-200 generated approximately 7.3 percent less environmental burden than the T-100. This was due to lower electrical energy being used per functional unit in the higher production capacity of the T-200. The extra additives in T-200 chip had very little effect on the environment performance of the two chips. The largest environmental effect in the production of two chips, shared 84 percent of all effects, was due to resources usage. The raw material phase generated the most environmental burden, this was due to environmental burden of the crude oil used to produce caprolactam, which was used as the raw materials for polyamide chip. The recovery phase generated the lowest environmental burden because low volume ratio of recovery water was used in production phase.

Key words: life cycle assessment; environmental assessment; polyamide 6; fiber; simapro 5.1

INTRODUCTION

The development of industrial technology has enabled the transformation of the environment in different ways, changing the nature and extent of the environmental impacts of industrial activities. Resource depletion, air, water and land pollution, are examples of the environmental problems which have emerged as a result of intensified interventions into the environment. Interest in the environmental qualities of the products has been increasing over the last 10 years. From the earlier focus on only a few product types and some parts of the process, especially production process. As a matter of fact, all of the process makes the transformation to the environment. Then it is becoming apparent with the increasing scientific awareness and move away from the narrow system that focus only at the production process. The new method of the environmental sustainability is realized, it is called Life Cycle Assessment (LCA).

The increase in society's awareness of environmental problems has sped up the development of assessment methods. An important method is Life Cycle Assessment (LCA) which is a tool for assessing the environmental impact of a product, process or service during its entire life cycle from the "cradle-to-grave". It may be used, for example, for product development and improvement, strategic planning, public policymaking and marketing. The LCA tool is e.g. used for finding the hot spots in the life cycle in order to be able to make the best decisions on minimizing the environmental burdens of the product, process or service. It is also used for comparisons between for instance different products regarding environmental impact. The main development of this method has taken place in the 1990s and it has been standardized in ISO standards no. 14040 to 14043. At present, LCA is widely used by many industrial to develop the environmental performance of product. Many sectors use LCA for their environmental assessment such as computer parts sector, electrical appliances sector, automotive sector, and textile sector. In this research the LCA tool is described with focus on the textile sector. Polyamide chip that used for fiber production (nylon6 fiber) is assessed by SimaPro 5.1, using Eco-indicator 95 and Eco-indicator 99 for evaluating the impacts.

Polyamide chip and fiber

Polyamides are a group of polymers characterized by a carbon chain with –CO-NH- groups interspersed at regular intervals along it. They are commonly referred to by the generic name "Nylon". For nylon 6 chips, they can be produced by condensation polymerization of caprolactam. About two thirds of the nylon produced is used for fibers (textiles, carpets, etc.). Polyamide chip will be used for spinning to polyamide fiber in the process called "Melt spinning process".

Melt-spinning process is the process that used for polyamide fiber spinning. It is the simplest method of fiber manufacture, mainly because it does not involve problems associated with the use of solvents. It is therefore the preferred method, provided the polymer gives a stable melt. When polyamide granules or chips form the starting material for melt spinning, they are first dried and then melt in the extruder. The homogenized and filtered melt is squirted through narrow channels into a quench chamber where solidification of the fluid filament bundles is achieved (Fig.2). Finally, spin finish is applied before the filament bundles are wound on tube rolls. In large modern plants, nylon is produced in continuous polymerization units in which the melt is directly transported from the final polymerize to the melt-spinning unit.

Life Cycle Assessment (LCA.)

The LCA method is an environmental assessment method, which focuses on the entire life cycle of a product from raw material acquisition to final product disposal. According to ISO 14040 to 14043 (Wenzel *et al.*, 1997), an LCA study must consist of four parts:

Goal and scope definition (ISO 14041)

The goal shall state the intended application, the reason for carrying out the study and the target audience. The scope describes the breadth, the depth and the detail of the study. It is important to define a functional unit and the system boundaries. The data quality requirements should be carefully specified.

-Function, functional unit and reference flow

A particularly important issue in product is comparison in the functional unit or comparison basis.

-Initial System Boundaries

It is clear that one cannot trace all inputs and outputs to a product systems, and that one has to define boundaries around the system. It is so clear that by excluding certain parts as they are outside the system boundaries, the results can be distorted.

-Data Quality Requirement

It is important to determine in advance what type of data we are looking for. In some studies we would like to get an average of all steel producers in the whole world. In other studies we would like to have only data from a single steel producer or from a group of steel producers.

Inventory analysis (ISO 14041)

Inventory analysis aims at determining flows of material and energy between the technical product system and the environmental. It involves data collection and calculation procedures for the technical process. Input data could be resources such as raw materials, energy or land and output data could be emissions to air, water or land.

Impact assessment (Life Cycle Impact Assessment, LCIA), (ISO 14042)

Impact assessment aims at evaluating the significance of potential environmental impact based on the result of the life cycle inventory analysis (LCA result). Impact assessment includes:

-Definition of impact categories and category indicators.

An important step is the selection of the appropriate impact categories. The choice is guided by the goal of the study.

Common impact categories (and indicators) are Climate change (CO_2 equivalents), Acidification (SO_2 equivalents), Eutrophication of waters (PO_4 equivalents), and Stratospheric ozone depletion (CFC-11 equivalents).

- Classification

The inventory result of an LCA usually contains hundreds of different emissions and resource extraction parameters. Once the relevant impact categories and determined, these LCI results must be assigned to these impact categories

-Characterization

Once the impact categories are defined and the LCI results are assigned to these impact categories, it is necessary to define characterization factors. These factors should reflect the relative contribution of an LCI result to the impact category indicator result. For example, on a time scale of 100 years the contribution of 1 kg. CH_4 to greenhouse effect is 42 times as high as the emission of 1 kg. CO_2. This means that if the characterization factor of CO_2 is 1, the characterization factor of CH_4 is 42. Thus, the impact category indicator result for greenhouse effect can be calculated by multiplying the LCI result with the characterization factor.

After characterization comes an optional step called weighting is used when there is a need to compare the relative important of various impact categories.

- Normalization

In normalization, the impact potentials and resource consumptions which have been determined are compared with an impact which is common for all impact categories. Normalization assists in assessing which of potential impacts are large and which are small by placing them in relation to the impacts from an average person.

- Weighing

The mutual seriousness of the impact categories is expressed in a set of weighting factors with one factor per impact category within each of the main group environment, resources and working environment. Then the weighting can be made by multiplying the normalized impact potential by the weighing factor which associated with the impact category or resource consumption.

Interpretation (ISO 14043)

Interpretation step means that conclusions are drawn and that recommendations can be given.

EXPERIMENTAL

Equipments

Two types of equipment that used in this research were personal computer (PC) and Simapro 5.1 software that was supplied by MTEC (National Metal and Materials Technology Center). The methods called Eco-indicator 95 and 99 were used to analyze the data.

Procedures

Investigate and study

The situation of nylon textile industries was investigated and SimaPro 5.1 software is employed to the life cycle assessment.

Goal and scope definition

The data of resource consumption, energy consumption, emission and waste from cradle-to-grave are collected during the entire life cycle of two types of polyamide chip used in nylon fiber production. The energy and environmental impact are evaluated in the steps of raw material process, production, transportation, use phase and disposal phase.

Inventory Analysis

The different input-output data from the company are collected and the flow charts of the process are created to show overall picture of life cycle of the products.

Impact assessment

The significance of potential environmental impact is evaluated based on the results of the life cycle inventory analysis.

Interpretation

The results from inventory analysis and impact assessment were analyzed and verified the conformability between the results, the goal and the scope definitions. The conclusions were drawn.

RESULTS AND DISCUSSION

Two types of polyamide chip are polyamide chip code T-100 and T-200. They are different in some physical properties such as T-200 has more light resistant than T-100 but both chips are used for producing polyamide fiber. Both of them are assessed from raw material phase, transportation phase, auxiliary phase, and production phase to the recovery phase as you can see from system boundary of Figure 4.1. The main raw material of the polyamide chip is the caprolactam. It is transported from Rayong province by 20 ton truck and imported from Japan by sea ship (see Table 4.1). The production phase can divide into three main steps. There are Lactam preparation and Polymerization process, Extraction process, and Drying process as you can see from Figure 4.1.

Firstly, some chemical is added into the lactam solution and mixed with the agitator in the Lactam preparation process. Lactam solution is polymerized to polymer in Polymerization process and it is cut to be the chip called O.G. chip (see

Figure 4.3). The second process is Extraction process (see Figure 4.5). Monomer and oligomer, which are not polymerized, are extracted from O.G. chip by hot water with centrifuge and chip from this process is called E-chip. Drying process is the last process of the production process, E-chip is dried in the vacuum dryer for reducing the moisture and increasing viscosity (see Figure 4.6). The production process of polyamide chip code T-100 and T-200 are the same but it is slightly different in some chemical that added in the Lactam preparation process. Two extra additives, which added in T-200 more than T-100, are $MnCl_2$ and $Na_2B_4O_7$ (see Figure 4.4).

In the recovery process, it is divided into two parts. They are Water waste and Mixing process (see Figure 4.1). From Water waste process, the extraction water from Extraction process are concentrated to be liquid called L.P.L. (see Figure 4.7) and sent to the Mixing process.

For auxiliary unit, it includes of Melting process, Depolymerization and condensation process, and Distillation process (Figure 4.2). Nylon waste and oligomer are melted in the Melting process and the molten waste is depolymerized and condensed to the A.D.L. in Depolymerization and Condensation process (see Figure 4.9). In the Distillation process, A.D.L. is added by some chemical and distilled to the A.P.L. and sent to the Mixing process in the recovery phase. From Figure 4.11, L.P.L. and A.P.L. are mixed to R.W.L. for recovering in the production process.

Goal and scope

The goal and scope of the study was to evaluate the environmental impact of two types of polyamide chip for the identification of the hot spot and to compare the environmental performance between two types of chip. The two types of chip coded T-100 chip and T-200 chip, were defined the functional unit as one ton of polyamide chip. The system boundary for the study covered from the raw material phase, transportation phase, production phase the recovery phase, and auxiliary phase as shown in Figure 4.1.

Inventory

The inventory of input data and emissions to environment in the life cycle of one ton of polyamide chips coded T-100 and T-200 were shown in Figure 4.12 and Figure 4.13 respectively. The transportation of the caprolactam that used as raw material was shown in Table 4.1 and the electricity that used in each process was shown in Table 4.2.

Impact assessment

In the study, contributions to eight impacts were analyzed by Eco-indicator 95 method. These eight impacts were greenhouse effect potential, ozone layer depletion, acidification potential, eutrophication potential, heavy metals generation, carcinogens potential, solid waste generation, and energy resources use. Figure 4.14-21 show the summary of each impact and the shares of each process on the impact. Table 4.3 and 4.4 show the total amount of environmental impact potentials and energy use in the life cycle of one ton of T-100 and T-200 chips.

The results showed that the most important phase with respect to environmental impacts is raw material phase. It is responsible for about 93 percent contributions to greenhouse effect potential, 81 percent contributions to acidification and eutrophication potential, and 86 percent contributions to energy resources use (see Figure 4.14, 4.16, 4.17, and 4.20). The contributions to these impacts are due to the emissions of caprolactam production and crude oil production that use as an initial raw material for caprolactam production in raw material phase for this study. The second important phase is production phase especially extraction process. It is responsible about 71 percent contributions to carcinogen potential, and 94 percent contributions to solid waste generation (see Figure 4.19 and 4.21). These impacts are due to the emissions from the material that use for producing water in Thailand because large amount of water was used in the extraction process.

- Greenhouse effect mostly comes from CO_2 emissions from the caprolactam production that used as raw material phase in this study. The remaining contributions mostly are due to CO_2 emission from electricity production.

- For Ozone layer depletion, the most important phase that affect to this impact is transportation phase. The emission of halon-1301 from diesel production for truck energy is the reason for 52 percent contributions to the impact. The second phase which generate 46 percent contributions to the impact is production phase especially extraction process. The effect is due to the tetrachloromethane emission from NaOH production which is used as raw material for producing water that used in the process.

- The main source of Acidification and Eutrophication potential is NO_x and SO_2 emissions from the material that used for caprolactam production. It is a reason that about 80 percent contributions to these impact come from raw material phase.

- Heavy metals generation comes from Melting process in auxiliary phase about 44 percent contributions and extraction process in production process about 34 percent contributions. The impact is due to Cd emission from Oligomer production that used in Melting process. For extraction process, the impact is due to Cd and Pb emission from NaOH production which use for producing water that use in the extraction process.

- Carcinogen potential is primarily due to fluoranthene emission from material which used in the water production for extraction process. The contribution is about three fourth of the total.

- The main source of Energy resources used comes from the using of crude oil for caprolactam production in raw material phase. This is the important phase that has about 86 percent contributions to the impact.

- For the last environmental impact, Solid waste generation is due to the waste from crude coal production that was used as initial raw material for producing water. It is a reason that extraction process has 94 percent contributions to this impact.

The contribution of production processes to the environmental effects was nearly similar between T-100 chip and T-200 chip as indicated in Figure 4.14-4.21. However, the total amount of each effect was different as observed from Figure 4.22.

In general, T-200 chip generated about approximately 7.3 percent less environmental burden than the T-100. This was due to lower electrical energy being used per functional unit in the higher production capacity of the T-200. This was because of more modern technology of T-200 production in production phase than T-100 production. The extra additives in T-200 chip had very little effect on the environment performance of the two chips. This was due to a very little amount of additives using per one ton of T-200 chip and very little more Mn and Cl^- emission to water in T-200 chip than T-100 chip (see Figure 4.22).

From Figure 4.23 and 4.24 show that although three processes are grouped in production phase, two processes are grouped in recovery phase, three processes are grouped in auxiliary phase, the raw material phase still generated the largest environmental burden, this was due to environmental burden of the crude oil used to produce caprolactam, which was used as the raw materials for polyamide chip. The recovery phase generated the lowest environmental burden because low volume ratio of recovery water was used in production phase. The second important phase that generated large environmental burden was production phase due to the largest contributions to carcinogen potential and solid waste generation from extraction phase.

From the single score of Eco-indicator 95 method, the method did not calculated the factor of energy resources use and solid waste generation at normalization and weighting steps as shown in Table 4.5 then it had some uncertainty of the final weight scores (single score). In the Eco-indicator 99 method, the resources factor was calculated in the normalization and weighting steps. Normalization and weighting steps were performed at what is known as a damage category level. There are three damage categories the final weighted scores:

1. *Human health.* This is measured in DALY (Disability adjusted life years); that is, the different disabilities caused by diseases are weighted.
2. *Ecosystem quality or ecotoxicity.* This is measured in PDF*m2yr, which is the Potentially Disappeared Fraction of plant species. In term of ecotoxicity, this is measured as the percentage of all species present in the environment living under toxic stress.

3. *Resources*. This final damage category is measured in MJ surplus energy

The total environmental impact of T-100 chip and T-200 chip that analyzed by Eco-indicator 99 method are shown in Table 4.6. Tables 4.7 and 4.8 show percent contributions to the impacts from each phase of T-100 and T-200 chip. The result shows the same trend between Eco-indicator 95 and 99 methods. The largest contributions to the environmental impact belong to raw material phase and the second largest contributions belong to the production phase. The normalization and weighting factor are displayed in Table 4.9. The damage assessment result shows that T-200 chip generated about approximately 6.7 percent less environmental damage than the T-100 chip (see Figure 4.25). It is shown that the result of Eco-indicator 99 analyzing is nearly the same as Eco-indicator 95 method analyzing.

From the final weight scores (see Figure 4.26), the result showed that the resources usage was the largest environmental burden of both of T-100 and T-200 chips. The result showed the same trend between T-100 and T-200 chips that the second largest impact was human health impact and the smallest impact is the ecosystem quality impact. Table 4.10 showed the percent contributions to three impacts that analyzed from life cycle of the two types of chip. The largest environmental effect in the production of two chips, shared 84 percent of all effects, was due to resources usage. T-100 generated environmental burden approximately 1.06 times of T-200 generated (see Figure 4.27).

On the whole, the largest contributions to these three environmental impacts belong to the raw material phase. The resource usage came from the crude oil use for the caprolactam production for this phase. The human health impact came from CO_2 emission from caprolactam production and NO_x emission from material production that used for producing caprolactam. For the ecosystem quality impact, the main source is the NO_x and SO_2 emission that came from material production which used to produce caprolactam. Then the raw material phase was the hot spot of the life cycle of the polyamide chip. The reason that T-200 generated lower environmental burden than T-100 generated was the lower use of caprolactam per life cycle (one ton) of T-200 chip than T-100 chip. The other reason was due to lower electrical energy being used per functional unit in the higher production capacity of the T-200.

The extra additives in T-200 chip had very little effect on the environment performance of the two chips.

CONCLUSION AND RECOMMENDATION

Life cycle assessment (LCA) was used to investigate, quantify, and compare environmental performance of two types of polyamide chip (T-100 and T-200) used for polyamide fiber production in Thailand. Simapro 5.1 software was used to analyze the environmental impact of the two products and identify the hot spot per one ton of each chip (functional unit) as the goal and scope of the study. The result from the impact assessment of Eco-indicator 95 and 99 methods showed that the hot spot of T-100 and T-200 life cycle was raw material phase. From the final weight score of Eco-indicator 99 methods, the largest environmental effect in the production of two chips, shared 84 percent of all effects, was due to resources usage. The main source was the crude oil use from the caprolactam production that used as raw material. Although there was no resource usage calculation in Eco-indicator 95 method, the raw material phase still remained the hot spot of the life cycle of chips. The reason was due to the largest contributions to the greenhouse effect and, acidification and eutrophication potential. The important phase that generated the second largest environmental burden was production phase especially extraction process, this was due to the emission from the NaOH production that used for producing water in Thailand. The recovery phase generated the lowest environmental burden because low volume ratio of recovery water was used in production phase. T-200 generated approximately 7.3 percent less environmental burden than the T-100. This was due to lower electrical energy being used per functional unit in the higher production capacity of the T-200. The extra additives in T-200 chip had very little effect on the environment performance of the two chips.

This article suggests the suitable way for improving the environmental performance is to reduce the water consumed in the extraction process such as applying the recycle system of water to use in the process again.

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REFERENCES

1. Gupta, V.B., and Kothari, V.K. (1997). Manufactured fibre technology. London: Chapman & Hall.
2. ISO 14040: Environmental management—life cycle assessment—principles and framework. Geneva: International Standard Organization; 1997.
3. ISO 14041: Environmental management—life cycle assessment—goal and scope definition and inventory analysis. Geneva: International Standard Organization; 1998.
4. ISO 14042: Environmental management—life cycle assessment—life cycle impact assessment. Geneva: International Standard Organization; 2000.
5. ISO 14043: Environmental management—life cycle assessment for Fuels and Chemicals, Commercialization of polylactide polymers, 9 May 2001
6. Wenzel, H., Havschild, M., and Alting, L. (1997). Environmental Assessment of products. London: Chapman & Hall.

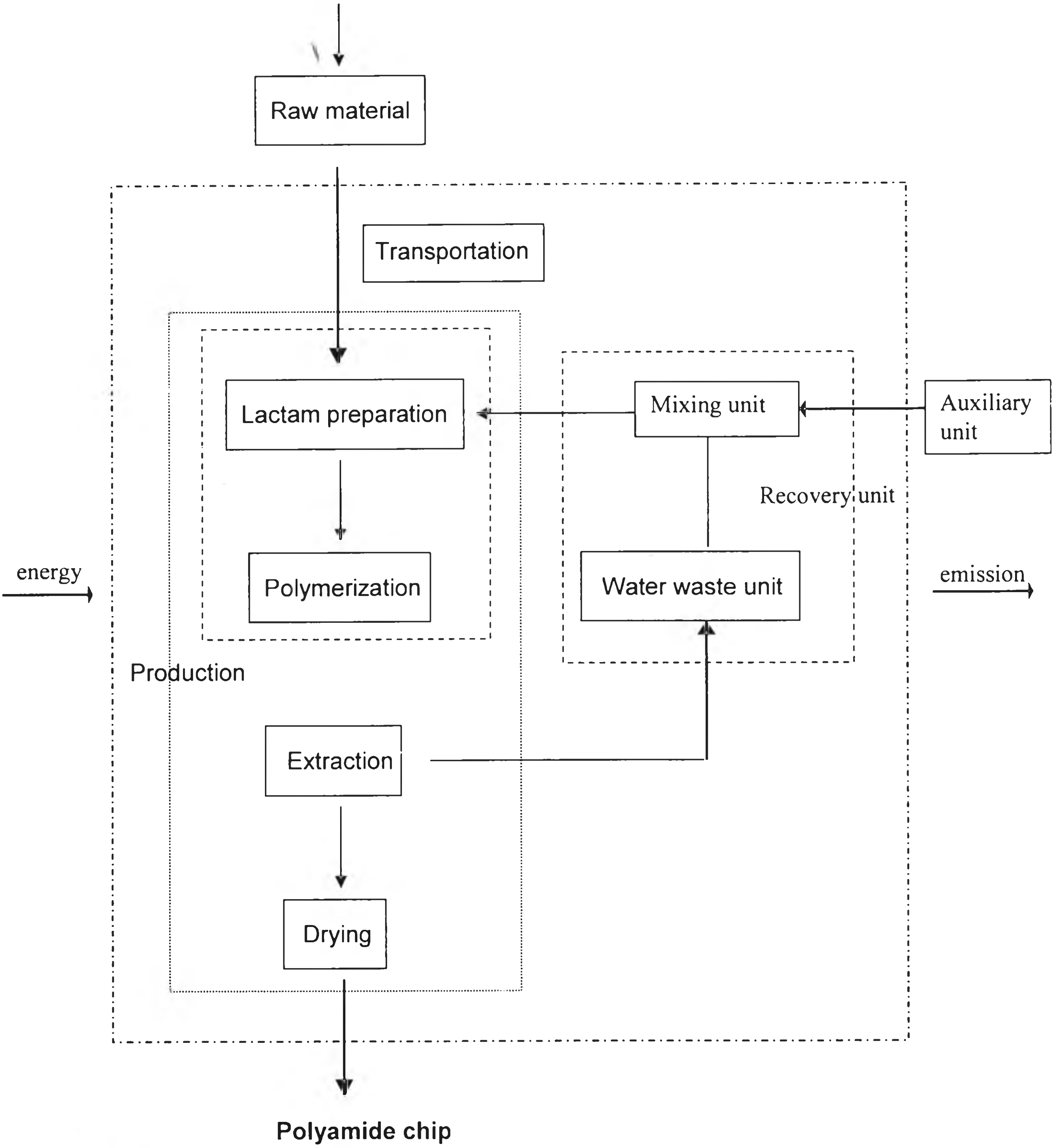


Figure 4.1 System Boundary of polyamide chip.

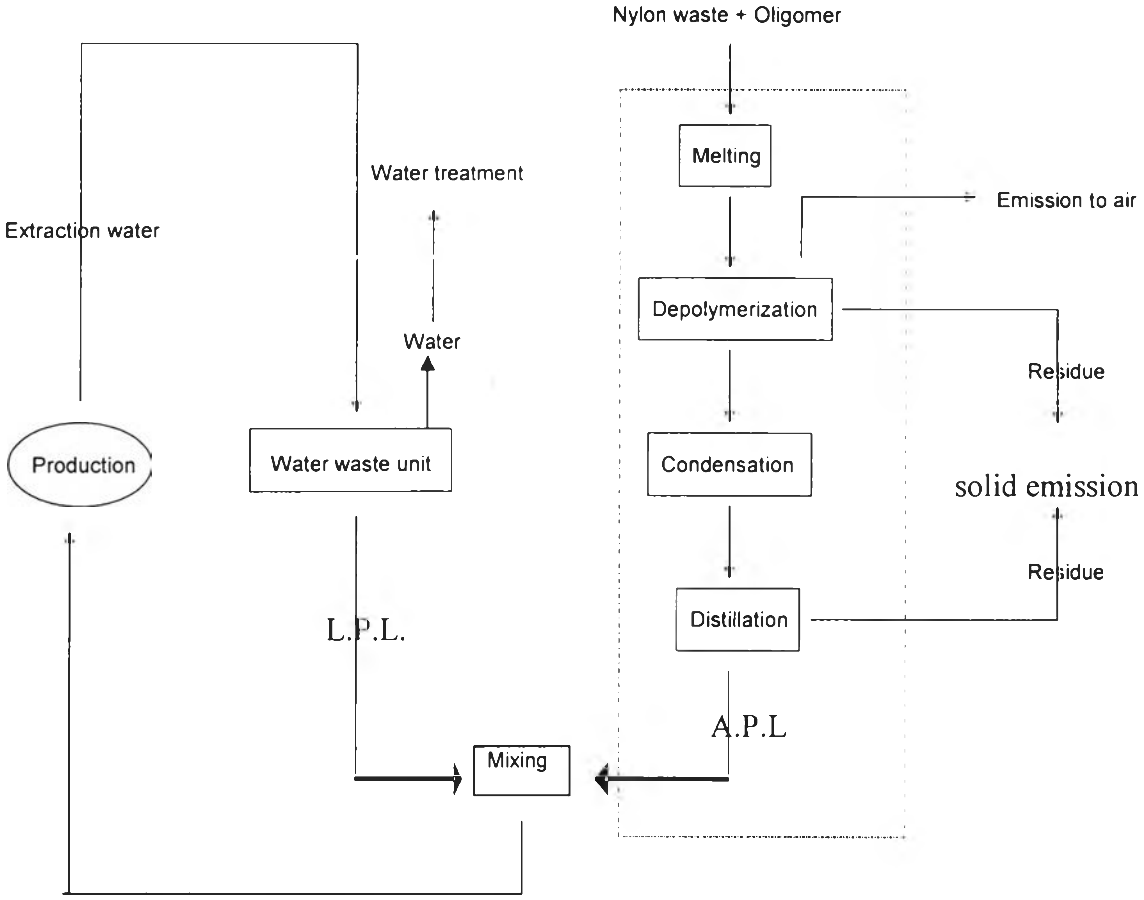
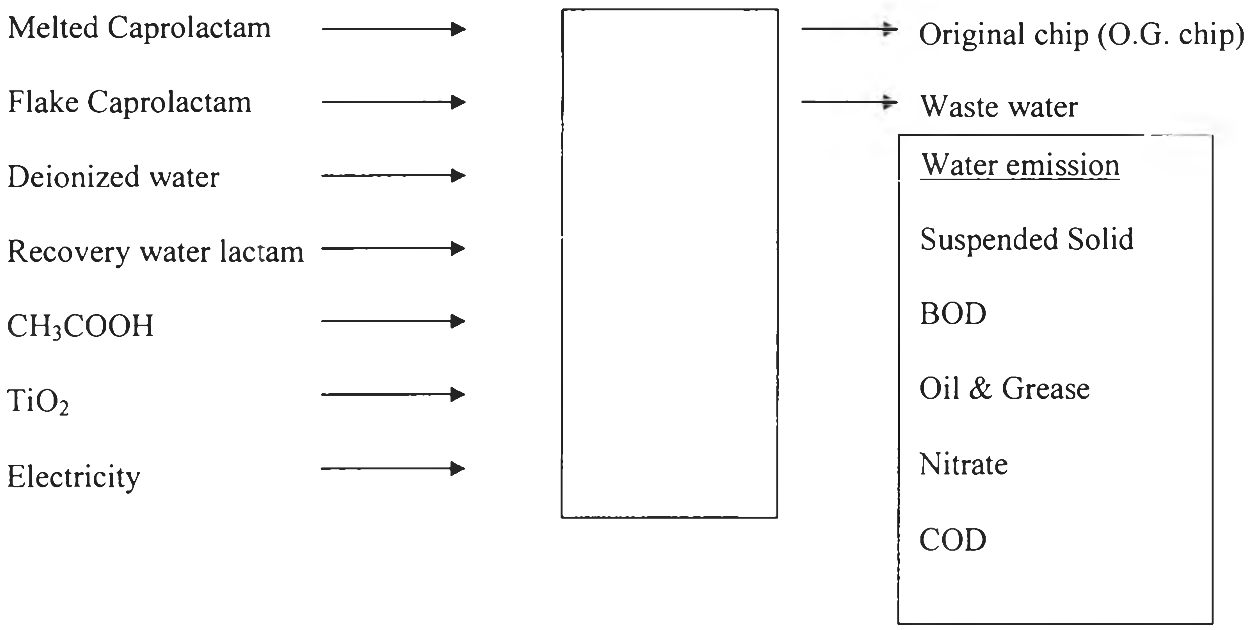


Figure 4.2 Detail of Auxiliary unit.

Production Phase

Lactam preparation + Polymerization process (T -100)



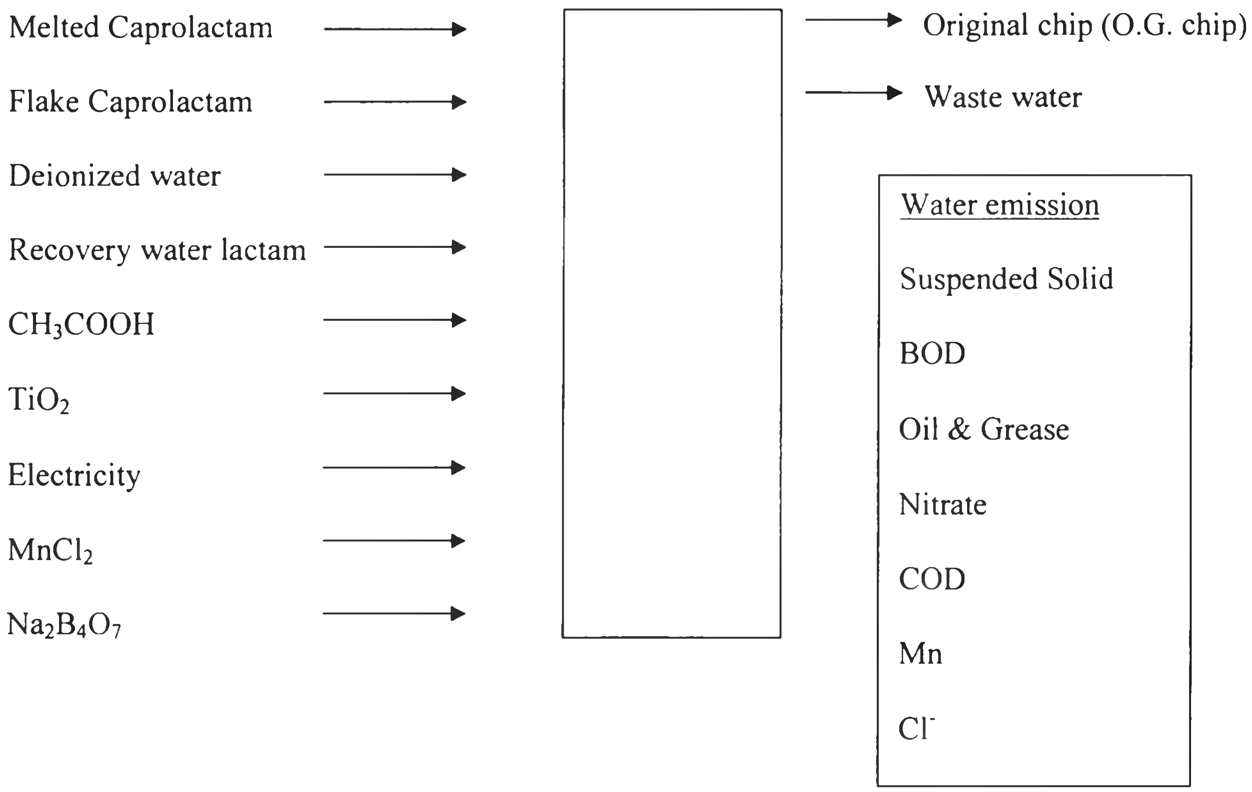
Input	T-100
MCPL	1.028ton
Flake L/C	0.114 ton
DI H_2O	0.128 ton
R.W.L.	0.127 ton
CH_3COOH	0.197 ton
TiO2	0.00003 ton
Electricity	752.245 kwh.

Output	T-100
O.G. chip	1.115 ton
Waste water	0.009 ton

H_2O emission	T-100
SS	17.979 μg.
BOD	156.695μg.
O & G	17,979 μg.
Nitrate	0.126 μg.
COD	0.899 μg.

Figure 4.3 Inventory of Lactam preparation and Polymerization process (T-100).

Lactam preparation + Polymerization process (T- 200)



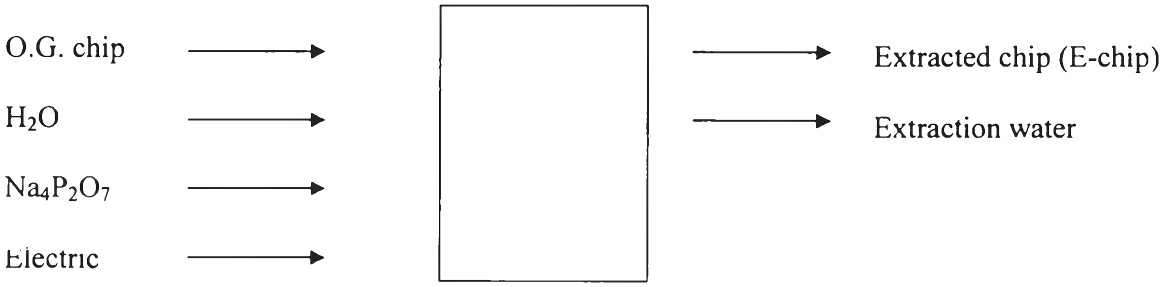
Input	T-200
MCPL	1.001 ton
Flake L/C	0.111 ton
DI H_2O	0.125 ton
R.W.L.	0.111 ton
CH_3COOH	0.189 ton
TiO2	0.004 ton
$MnCl_2$	0.048 kg.
$Na_2B_4O_7$	22.388 cc.
Electricity	351.2 kwh.

Output	T-200
O.G. chip	1.112 ton
Waste water	0.009 ton

H_2O emission	T-200
SS	17.502 µg.
BOD	152.529µg.
O & G	17.502 µg.
Nitrate	0.122 µg.
COD	0.875 µg.
Mn	0.149 µg.
Cl-	0.875 µg.

Figure 4.4 Inventory of Lactam preparation and Polymerization process (T-200).

Extraction Process

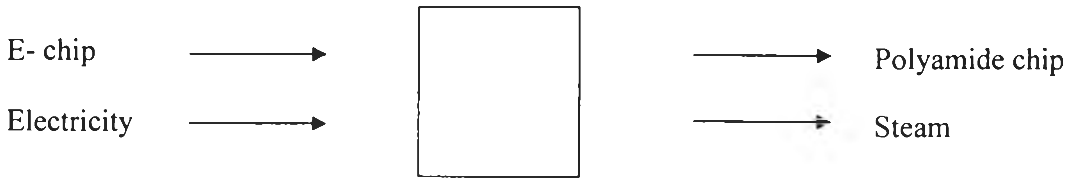


Input	T-100	T-200
O.G. chip	1.115 ton	1.112 ton
H_2O	3.038 ton	2.672 ton
$Na_4P_2O_7$	0.596 ton	0.552 kg.
Electricity	203.983 kwh.	44.2 kwh.

Output	T-100	T-200
E- chip	1.115 ton	1.112 ton
Extraction H_2O	2.673 ton	2.672 ton

Figure 4.5 Inventory of Extraction process.

Drying process



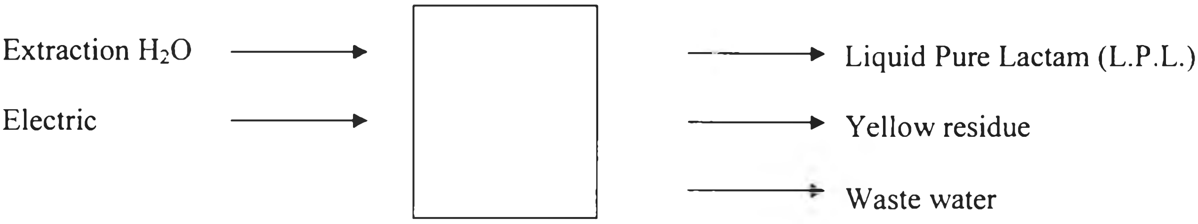
Input	T-100	T-200
E- chip	1.115 ton	1.11194 ton
Electricity	273.208 kwh.	59.2 kwh.

Output	T-100	T-200
PA- chip	1 ton	1 ton
Steam	0.115 ton	0.112 ton

Figure 4.6 Inventory of Drying process.

Recovery Phase

Water waste process

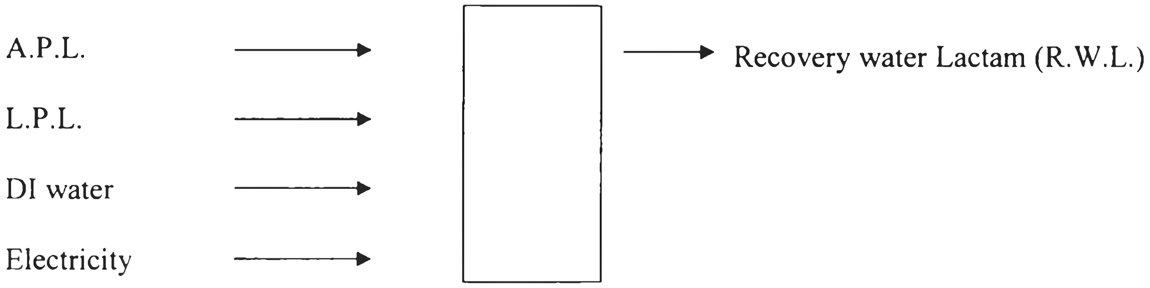


Input	T-100	T-200
Extraction H_2O	2.409 ton	2.110 ton
Electricity	16.241 kwh.	14.228 kwh.

Output	T-100	T-200
L.P.L.	0.079 ton	0.069 ton
Yellow residue	0.018 ton	0.016 ton
H_2O	2.294 ton	2.009 ton

Figure 4.7 Inventory of Water waste process.

Mixing process



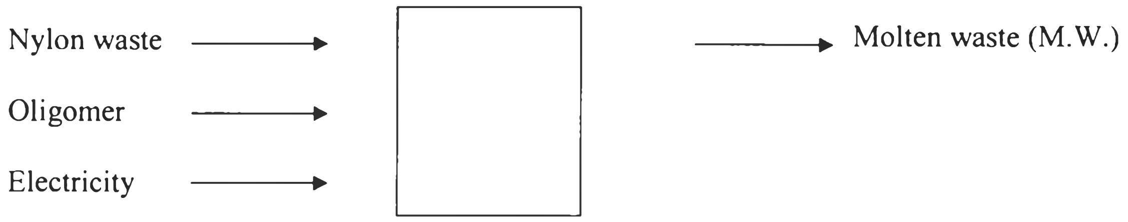
Input	T-100	T-200
A.P.L.	0.047 ton	0.041 ton
L.P.L.	0.079 ton	0.069 ton
DI H_2O	0.015 ton	0.013 ton
Electricity	7.631 kwh.	6.685 kwh.

Output	T-100	T-200
R.W.L.	0.127 ton	0.111 ton

Figure 4.8 Inventory of Mixing process.

Auxiliary unit

Melting process

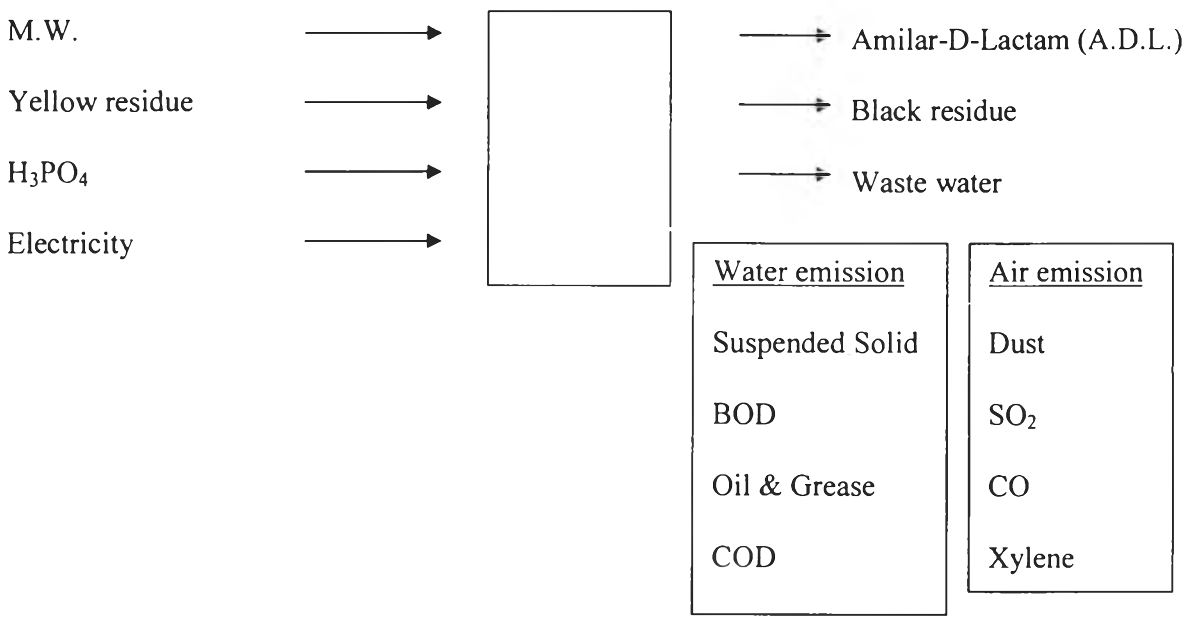


Input	T-100	T-200
Nylon waste	0.033 ton	0.029 ton
Oligomer	0.006 ton	0.005 ton
Electricity	55.483 kwh.	48.600 kwh.

Output	T-100	T-200
M.W.	0.039 ton	0.034 ton

Figure 4.9 Inventory of Melting process.

Depolymerization + Condensation process



Input	T-100	T-200
M.W.	0.039 ton	0.034 ton
Yellow residue	0.018 ton	0.016 ton
H_3PO_4	3.468 kg.	3.038 kg.
Electricity	56.506 kwh.	49.494 kwh.

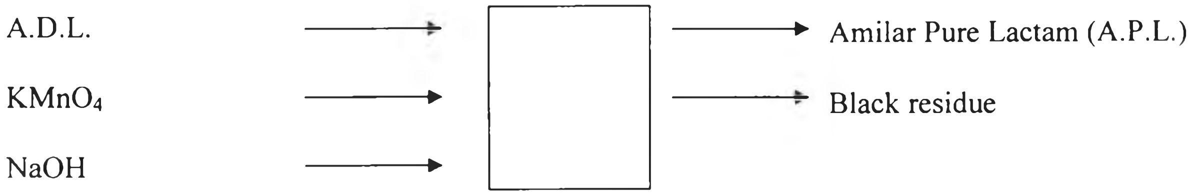
Output	T-100	T-200
A.D.L.	0.052 ton	0.046 ton
Black residue	0.004 ton	0.004 ton
H_2O	0.002 ton	0.001 ton

Air emission	T-100	T-200
Dust (TSP)	19.484 g.	17.066 g.
SO2	1.299 mg.	1.138 mg.
NO_x	87.556 g.	76.691 g.
CO	2.872 mg.	2.516 mg.
Xylene	0.113 mg.	0.099 mg.

H_2O emission	T-100	T-200
SS	12.332 μg.	10.802 μg.
BOD	0.059 mg.	0.052 mg.
O & G	12.949 μg.	11.342 μg.
COD	0.154 μg.	0.135 μg.

Figure 4.10 Inventory of Depolymerization and Condensation process.

Distillation process

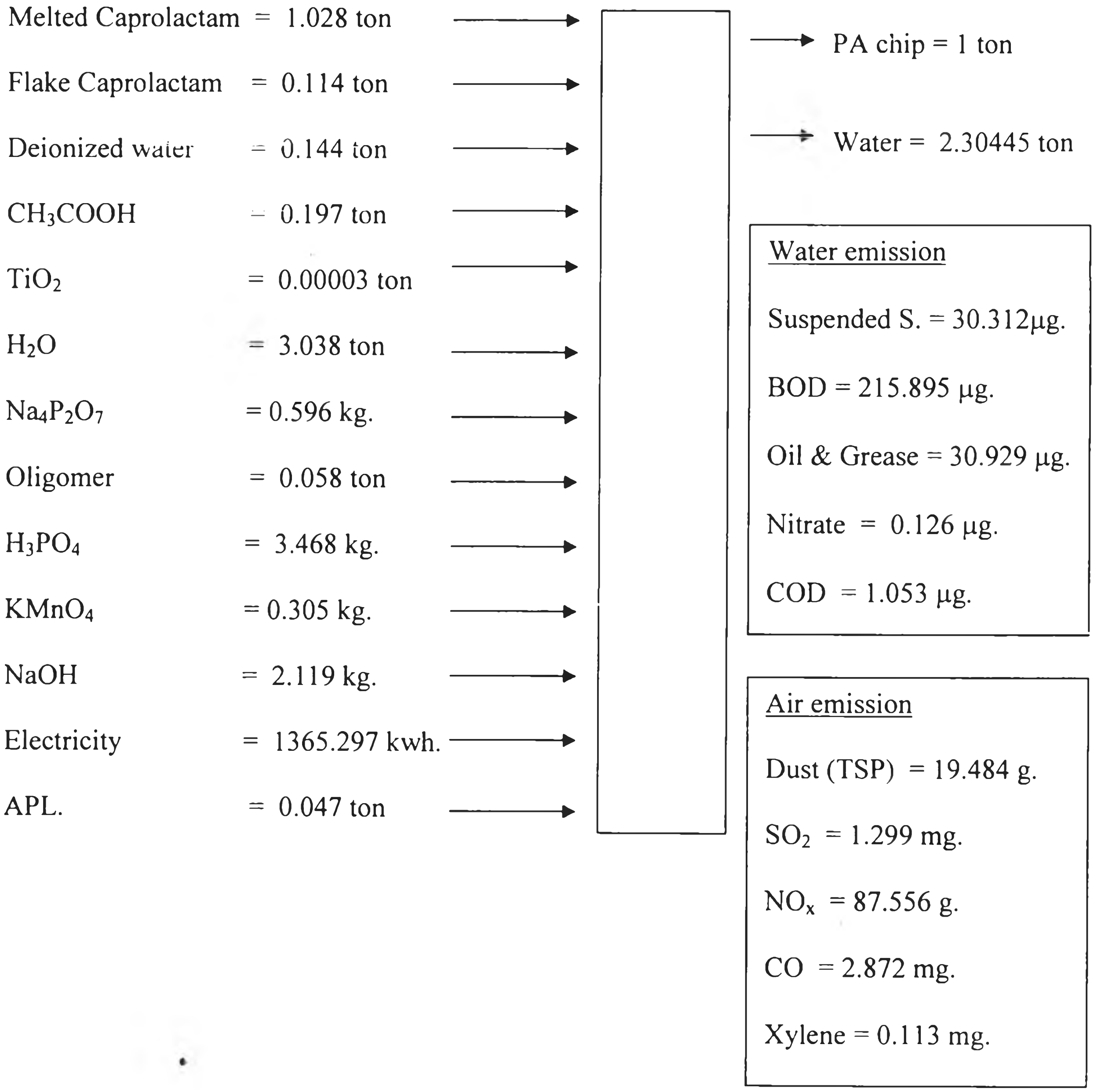


Input	T-100	T-200
A.D.L.	0.052 ton	0.046 ton
$KMnO_4$	0.305 kg.	0.267 kg.
NaOH	2.119 kg.	1.857 kg.

Output	T-100	T-200
A.P.L.	0.047 ton	0.041 ton
Black residue	0.004 ton	0.004 ton

Figure 4.11 Inventory of Distillation process.

Inventory of Polyamide chip code T-100



Melted Caprolactam = 1.028 ton

Flake Caprolactam = 0.114 ton

Deionized water = 0.144 ton

CH_3COOH = 0.197 ton

TiO_2 = 0.00003 ton

H_2O = 3.038 ton

$Na_4P_2O_7$ = 0.596 kg.

Oligomer = 0.058 ton

H_3PO_4 = 3.468 kg.

$KMnO_4$ = 0.305 kg.

NaOH = 2.119 kg.

Electricity = 1365.297 kwh.

APL. = 0.047 ton

PA chip = 1 ton

Water = 2.30445 ton

Water emission

Suspended S. = 30.312μg.

BOD = 215.895 μg.

Oil & Grease = 30.929 μg.

Nitrate = 0.126 μg.

COD = 1.053 μg.

Air emission

Dust (TSP) = 19.484 g.

SO_2 = 1.299 mg.

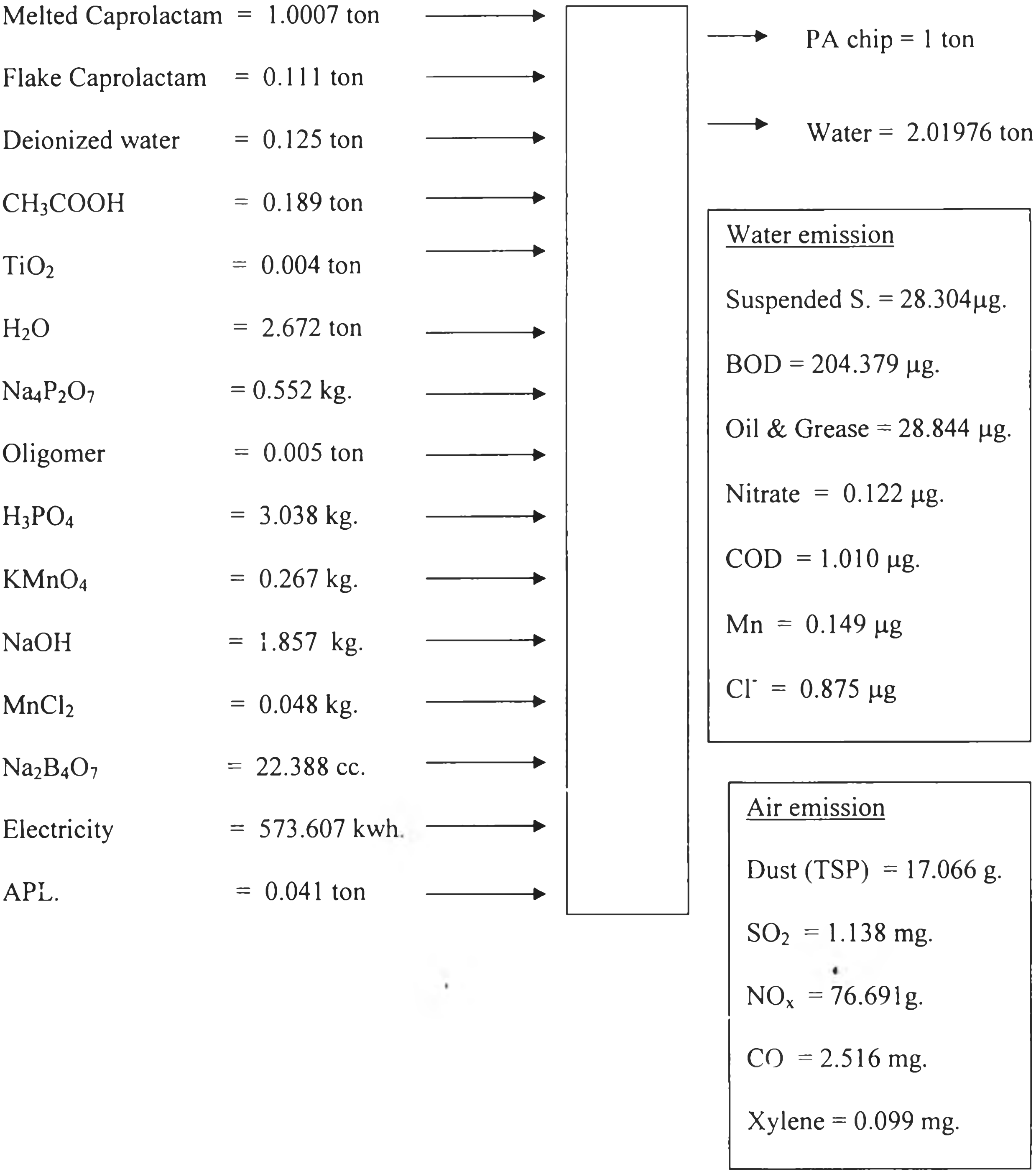
NO_x = 87.556 g.

CO = 2.872 mg.

Xylene = 0.113 mg.

Figure 4.12. Inventory of life cycle of polyamide chip code T-100.

Inventory of Polyamide chip code T-200



Melted Caprolactam = 1.0007 ton

Flake Caprolactam = 0.111 ton

Deionized water = 0.125 ton

CH_3COOH = 0.189 ton

TiO_2 = 0.004 ton

H_2O = 2.672 ton

$Na_4P_2O_7$ = 0.552 kg.

Oligomer = 0.005 ton

H_3PO_4 = 3.038 kg.

$KMnO_4$ = 0.267 kg.

NaOH = 1.857 kg.

$MnCl_2$ = 0.048 kg.

$Na_2B_4O_7$ = 22.388 cc.

Electricity = 573.607 kwh.

APL. = 0.041 ton

PA chip = 1 ton

Water = 2.01976 ton

Water emission

Suspended S. = 28.304µg.

BOD = 204.379 µg.

Oil & Grease = 28.844 µg.

Nitrate = 0.122 µg.

COD = 1.010 µg.

Mn = 0.149 µg

Cl^- = 0.875 µg

Air emission

Dust (TSP) = 17.066 g.

SO_2 = 1.138 mg.

NO_x = 76.691g.

CO = 2.516 mg.

Xylene = 0.099 mg.

Figure 4.13 Inventory of life cycle of polyamide chip code T-200.

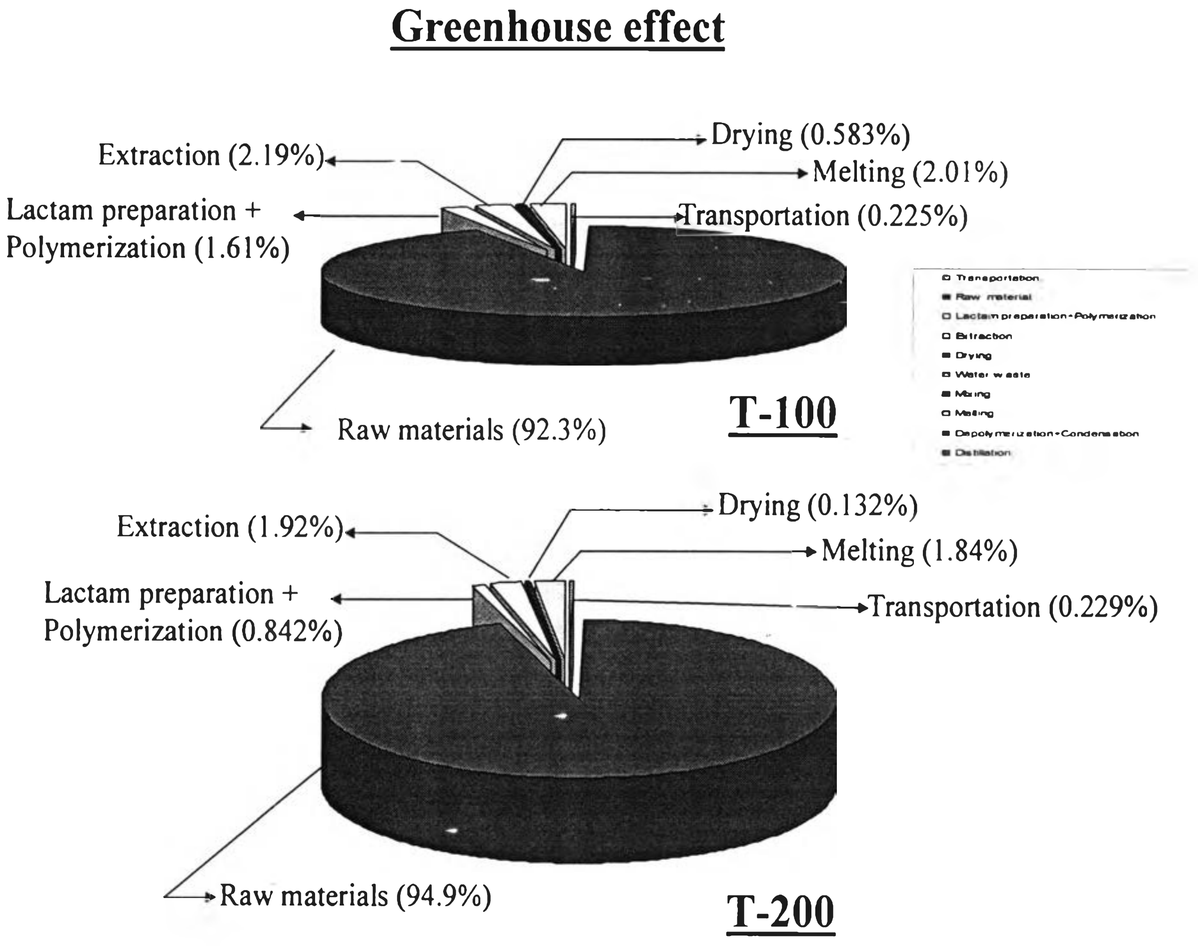


Figure 4.14 Percent contribution of each phase to greenhouse effect.

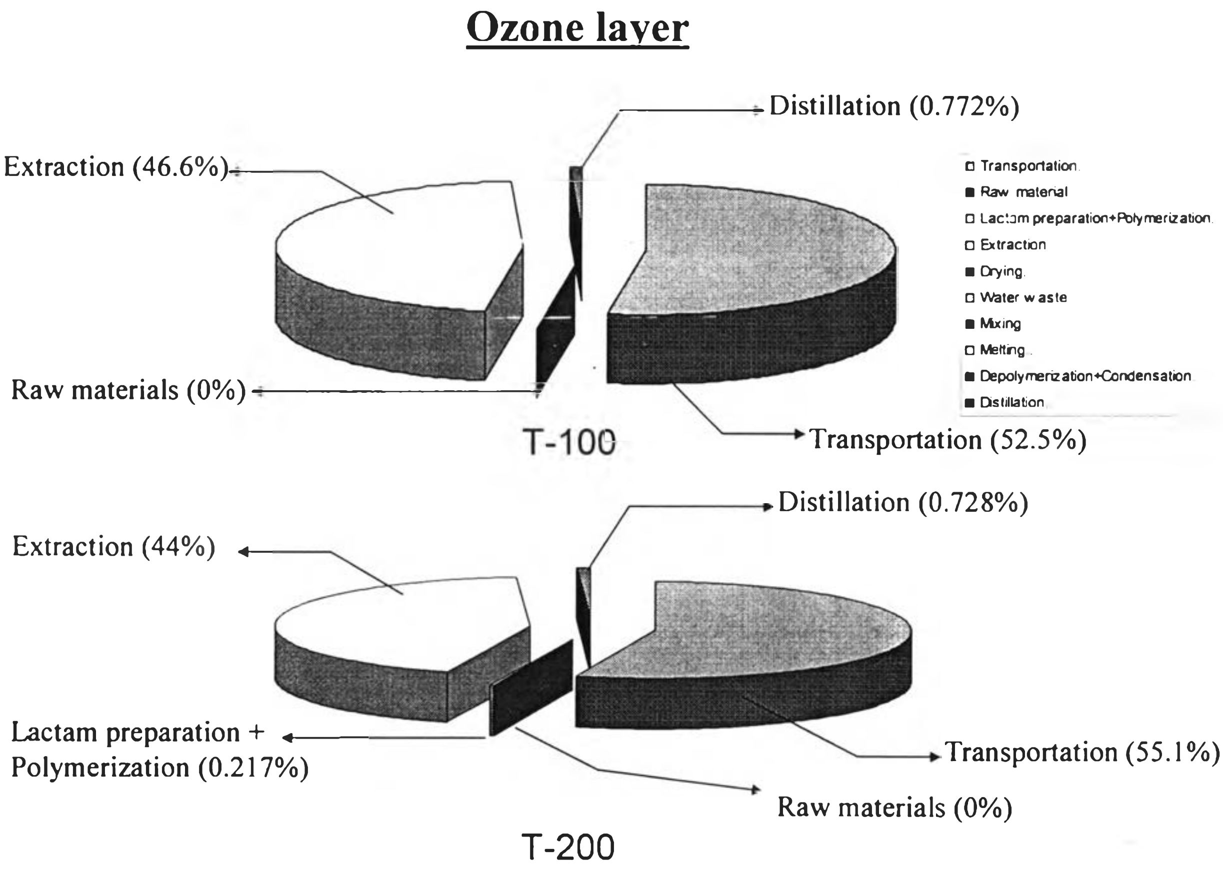


Figure 4.15 Percent contribution of each phase to ozone layer depletion.

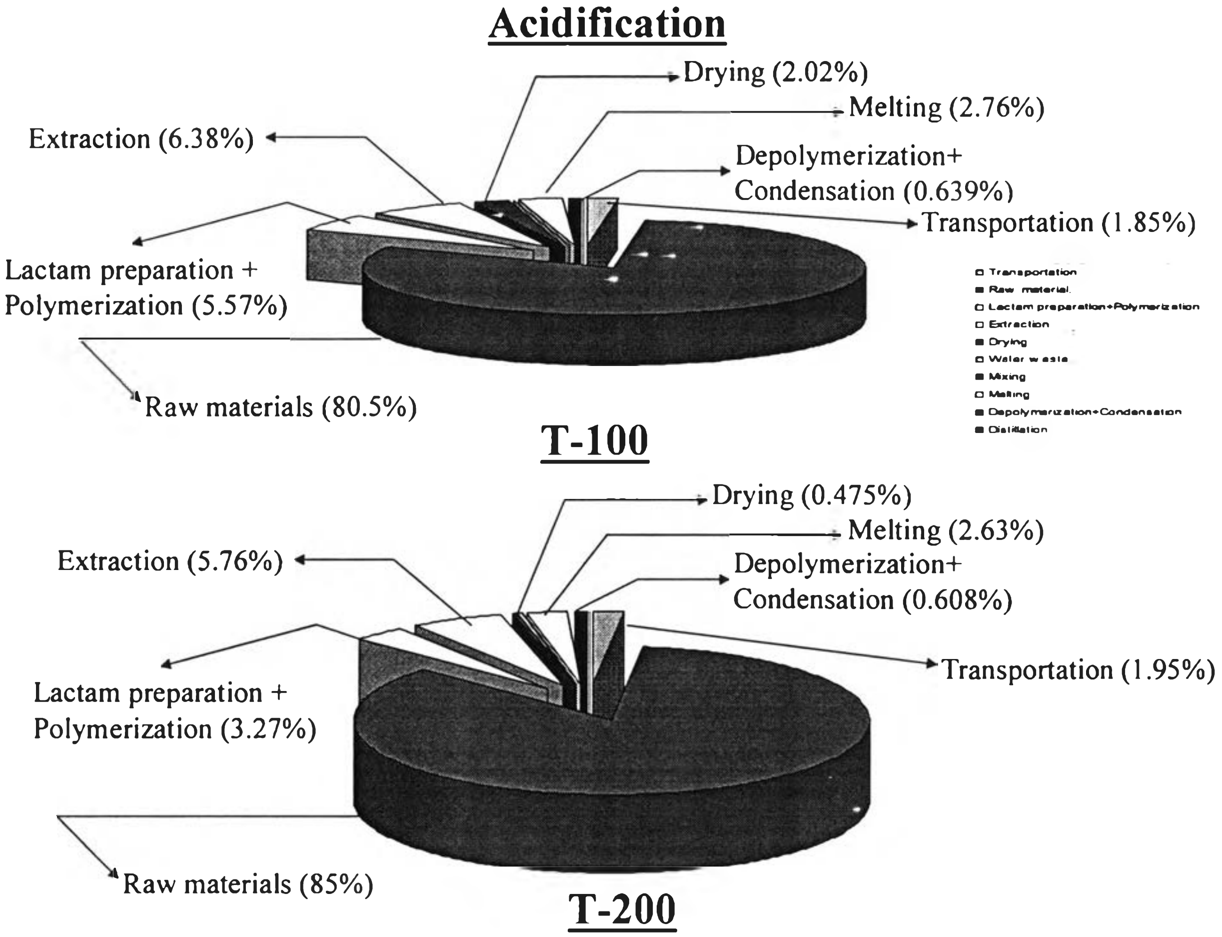


Figure 4.16 Percent contribution of each phase to acidification potential.

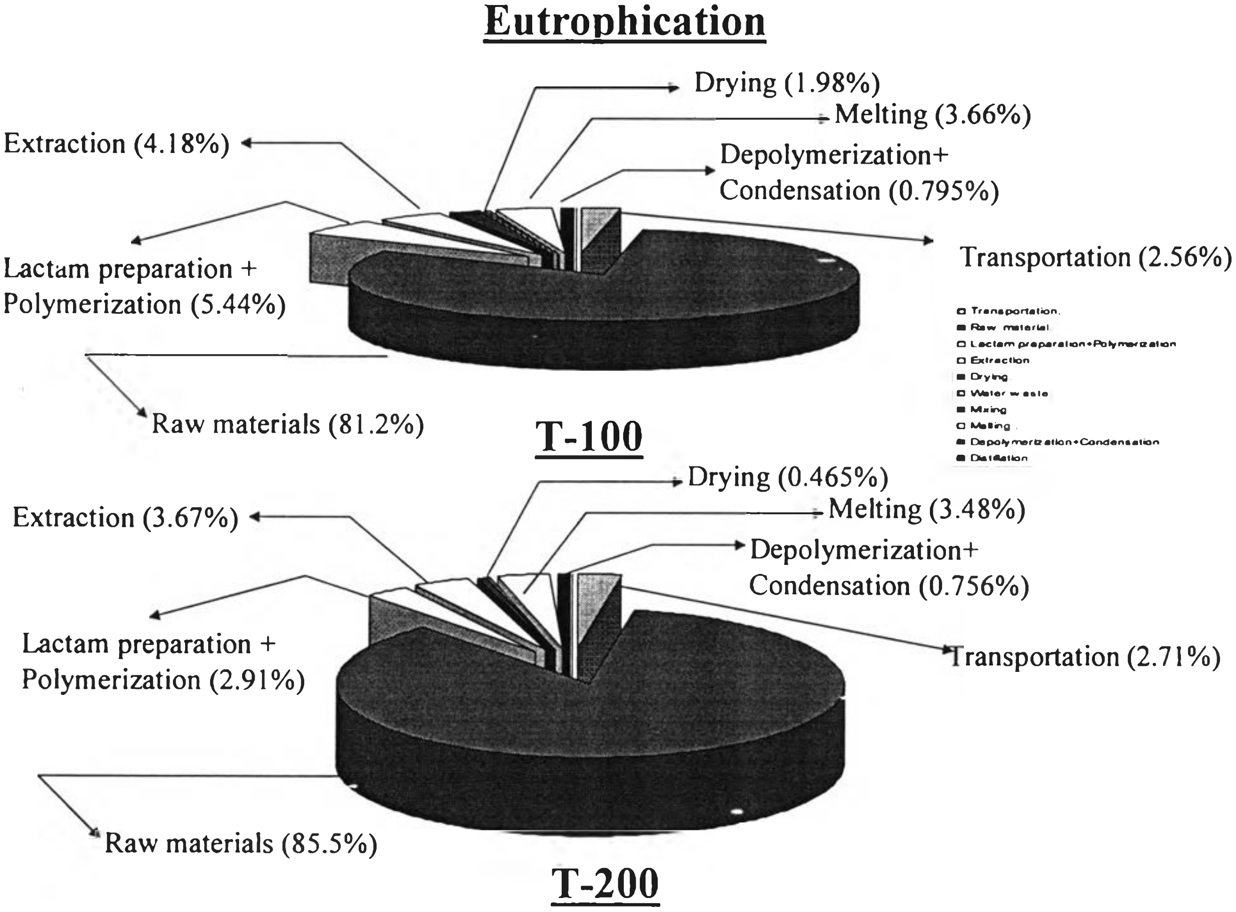


Figure 4.17 Percent contribution of each phase to eutrophication potential.

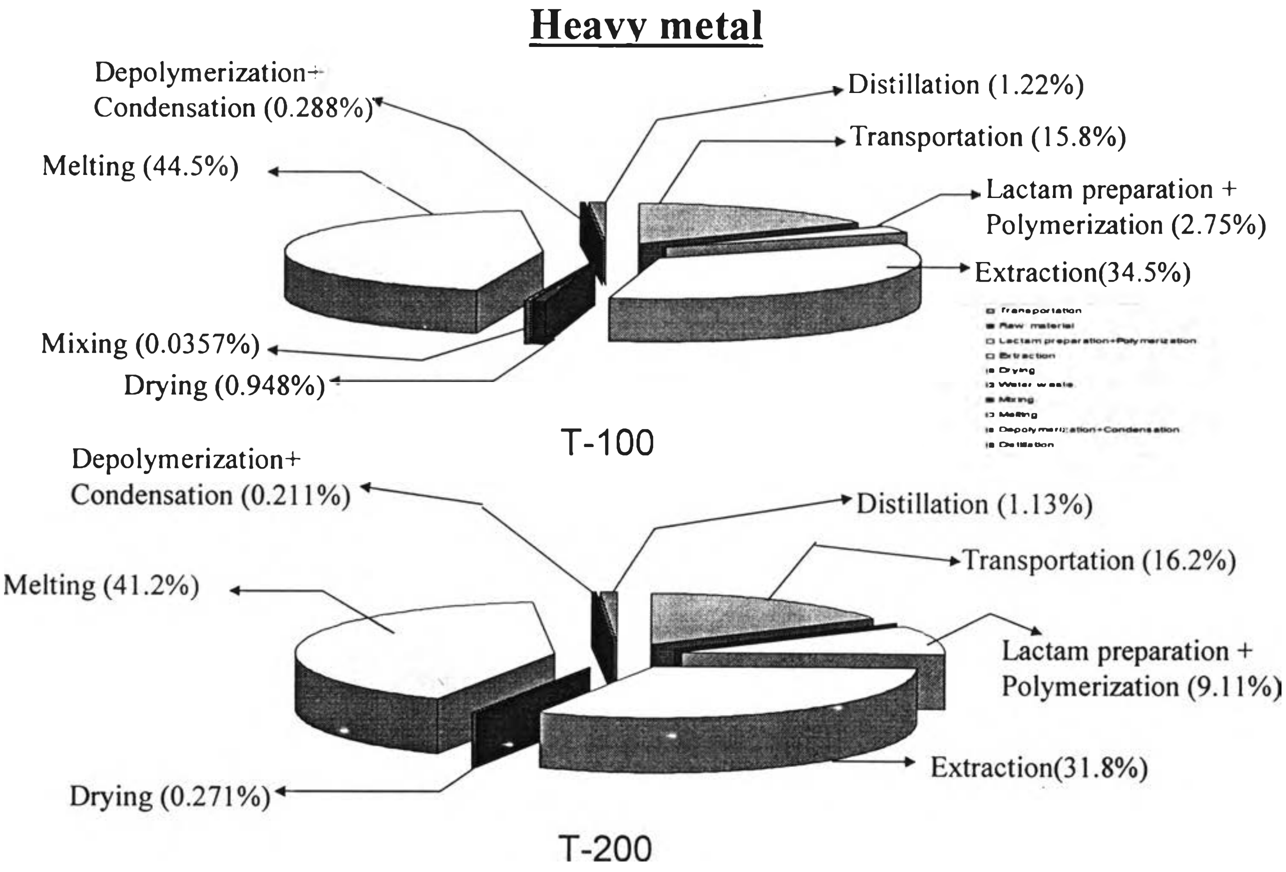


Figure 4.18 Percent contribution of each phase to heavy metal generation.

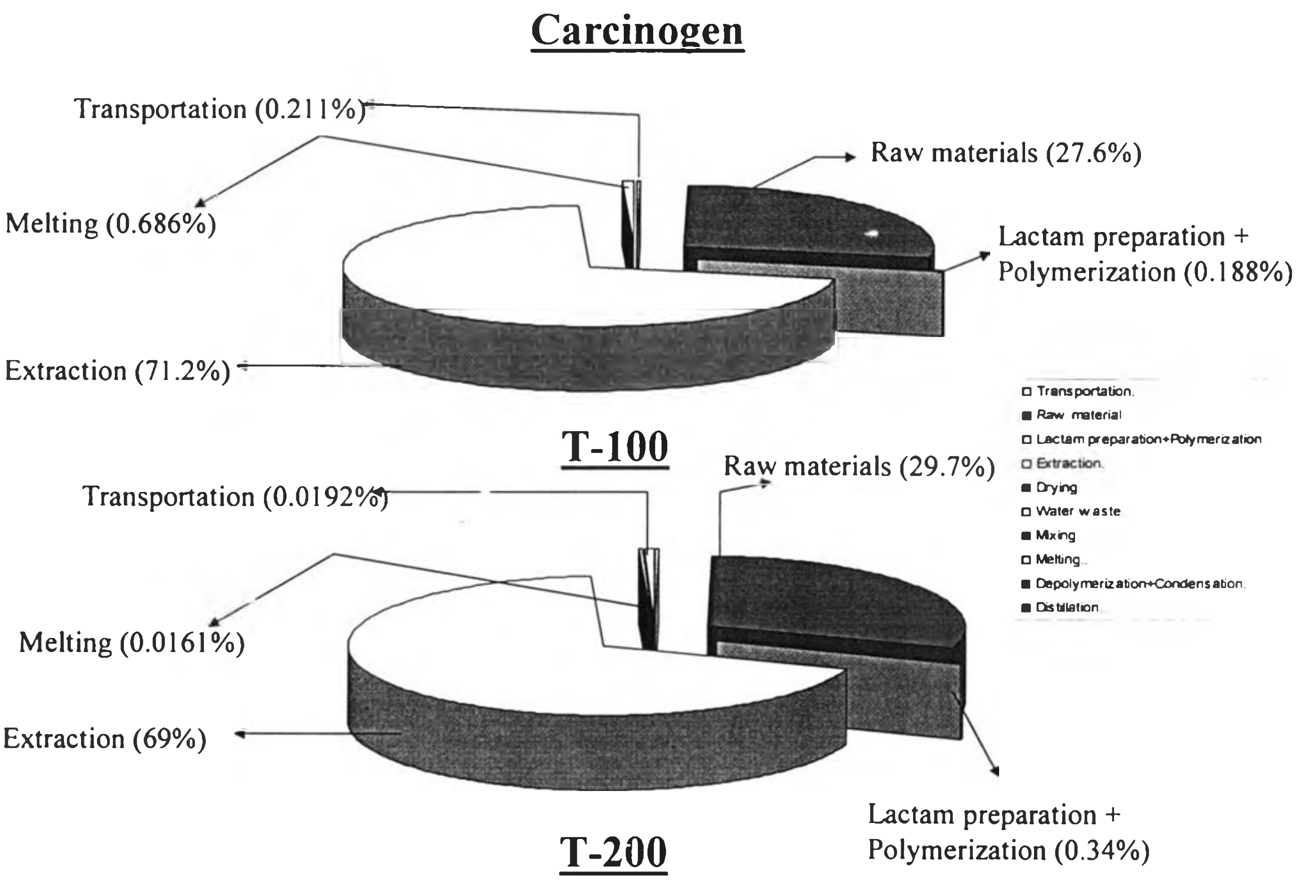


Figure 4.19 Percent contribution of each phase to carcinogen potential.

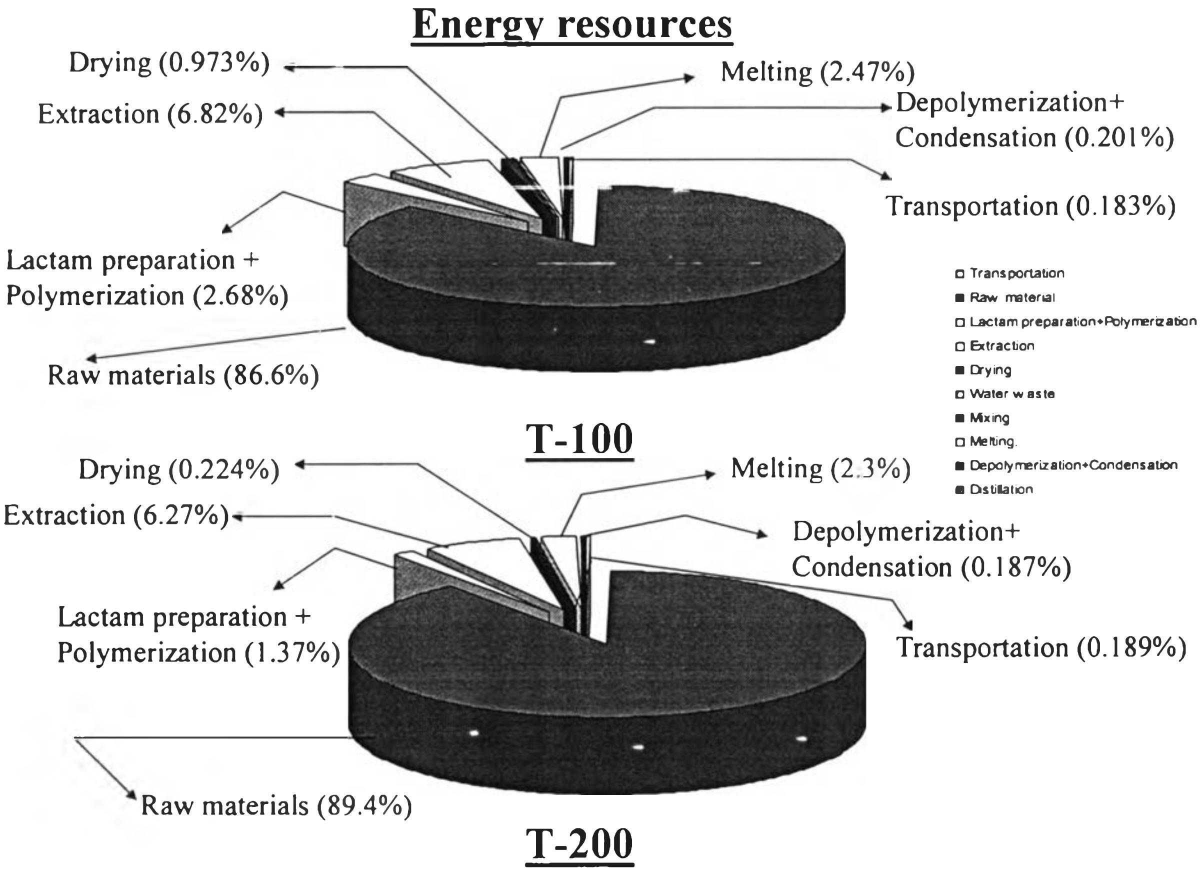


Figure 4.20 Percent contribution of each phase to energy resources use.

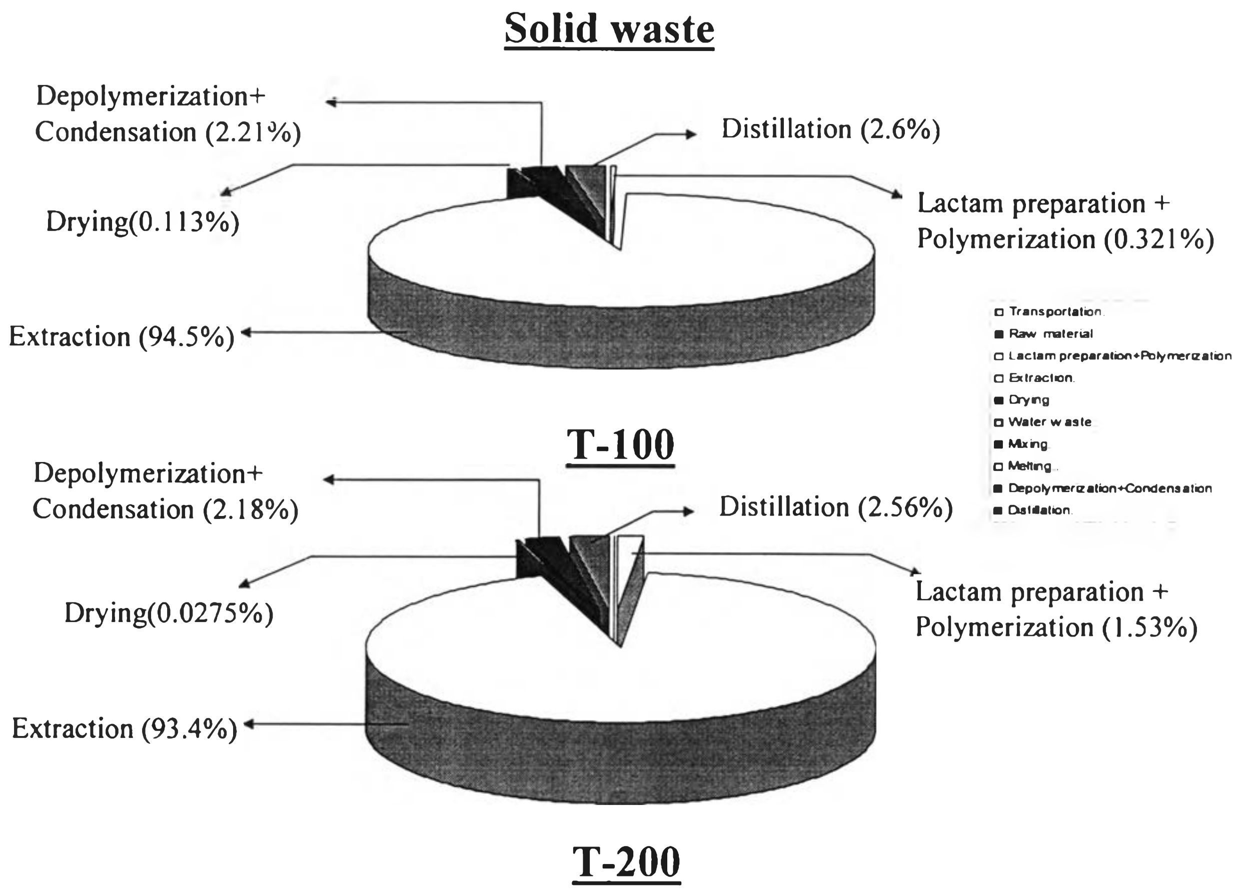


Figure 4.21 Percent contribution of each phase to solid waste generation.

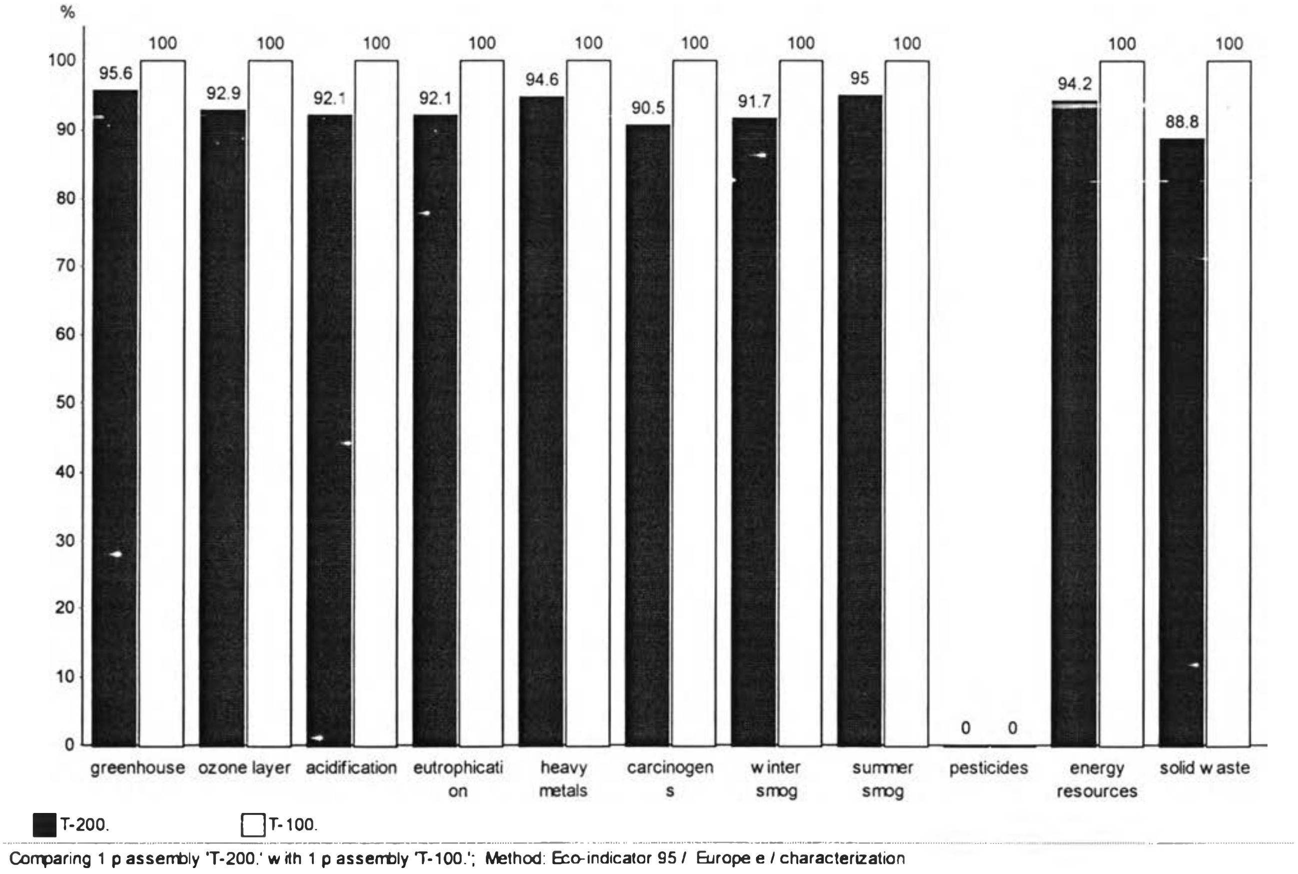


Figure 4.22 The comparison of the total amount of environmental impact between T-100 and T-200 chips by Eco-indicator 95.

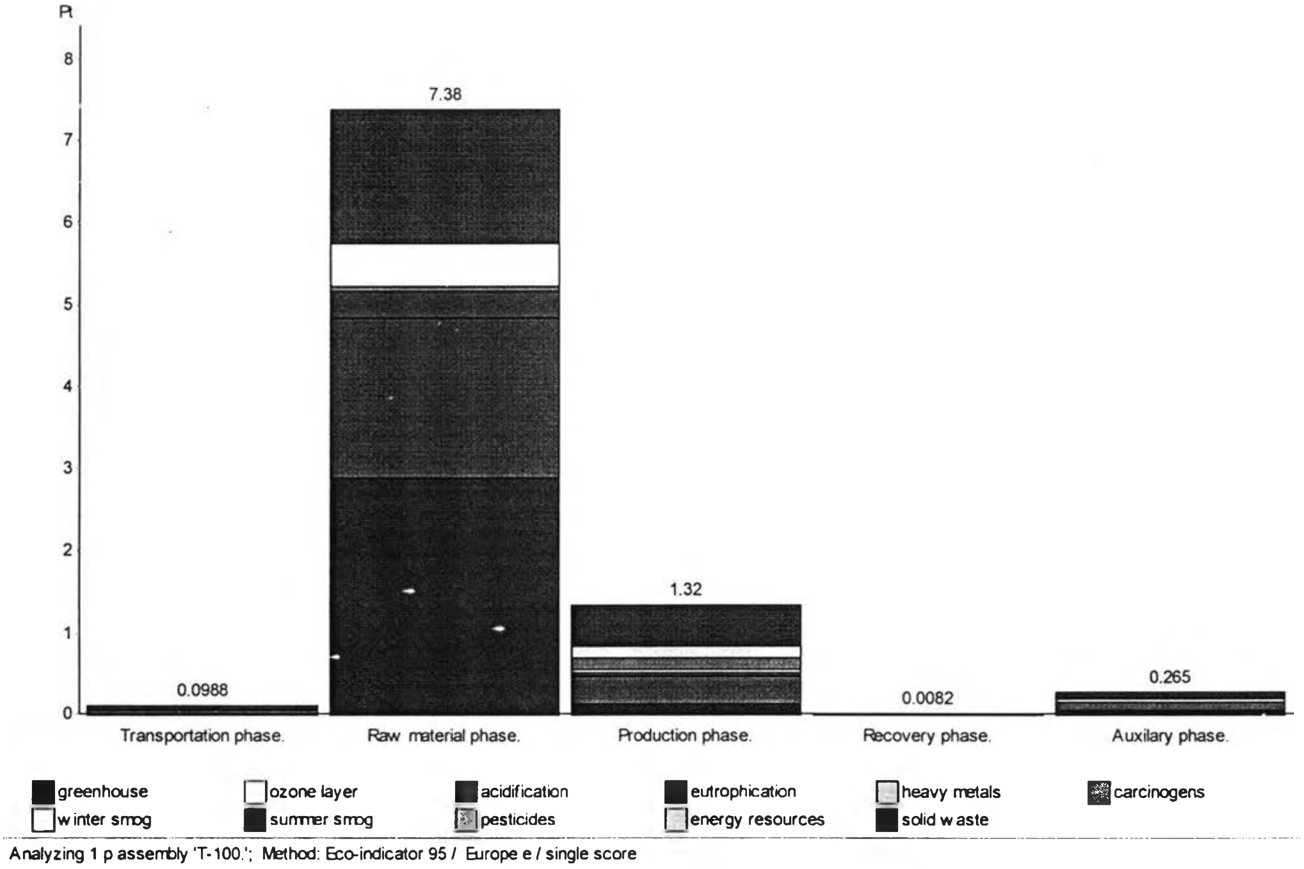
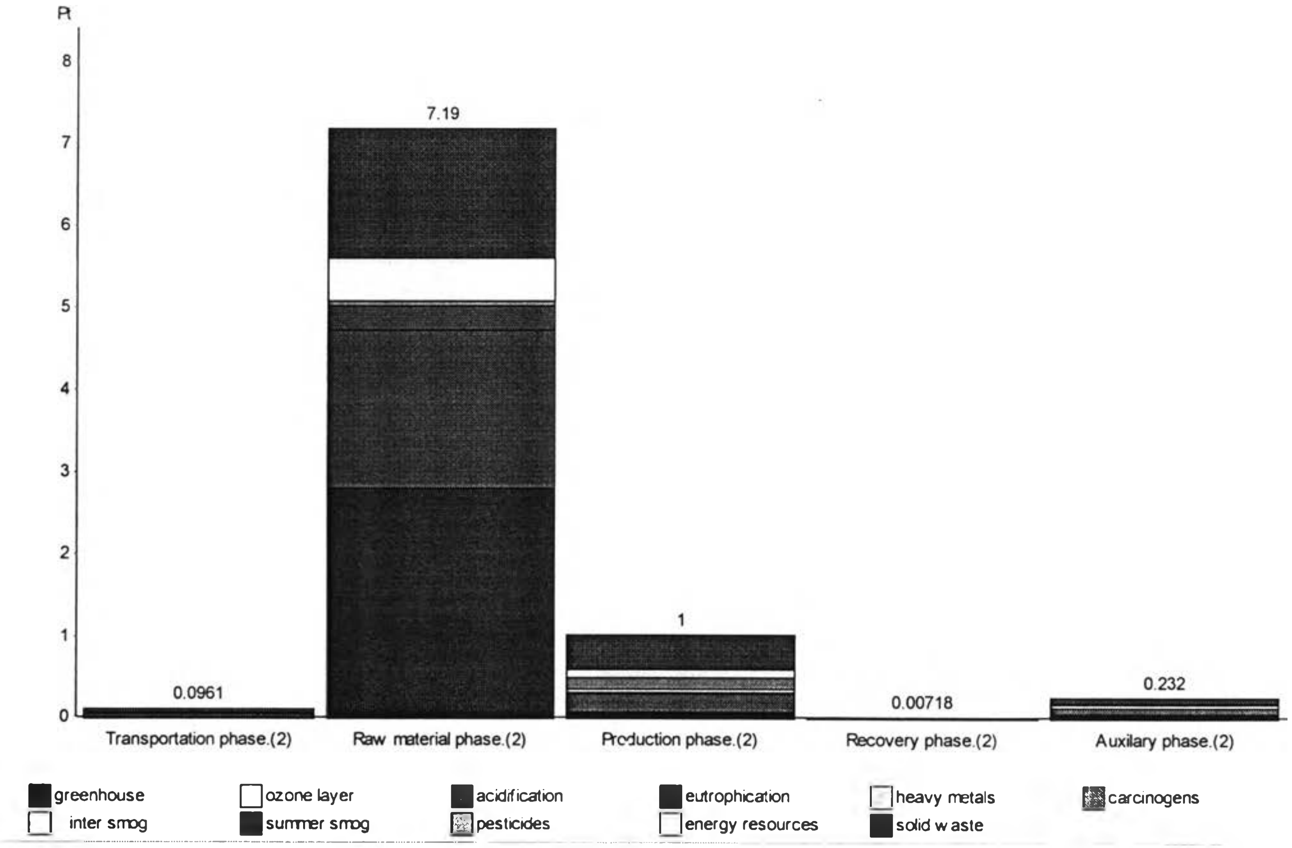


Figure 4.23 The comparison of the total amount of environmental impact between each phase of T-100 chip.



Analyzing 1 p assembly 'T-200.'; Method: Eco-indicator 95 / Europe e / single score

Figure 4.24 The comparison of the total amount of environmental impact between each phase of T-200 chip.

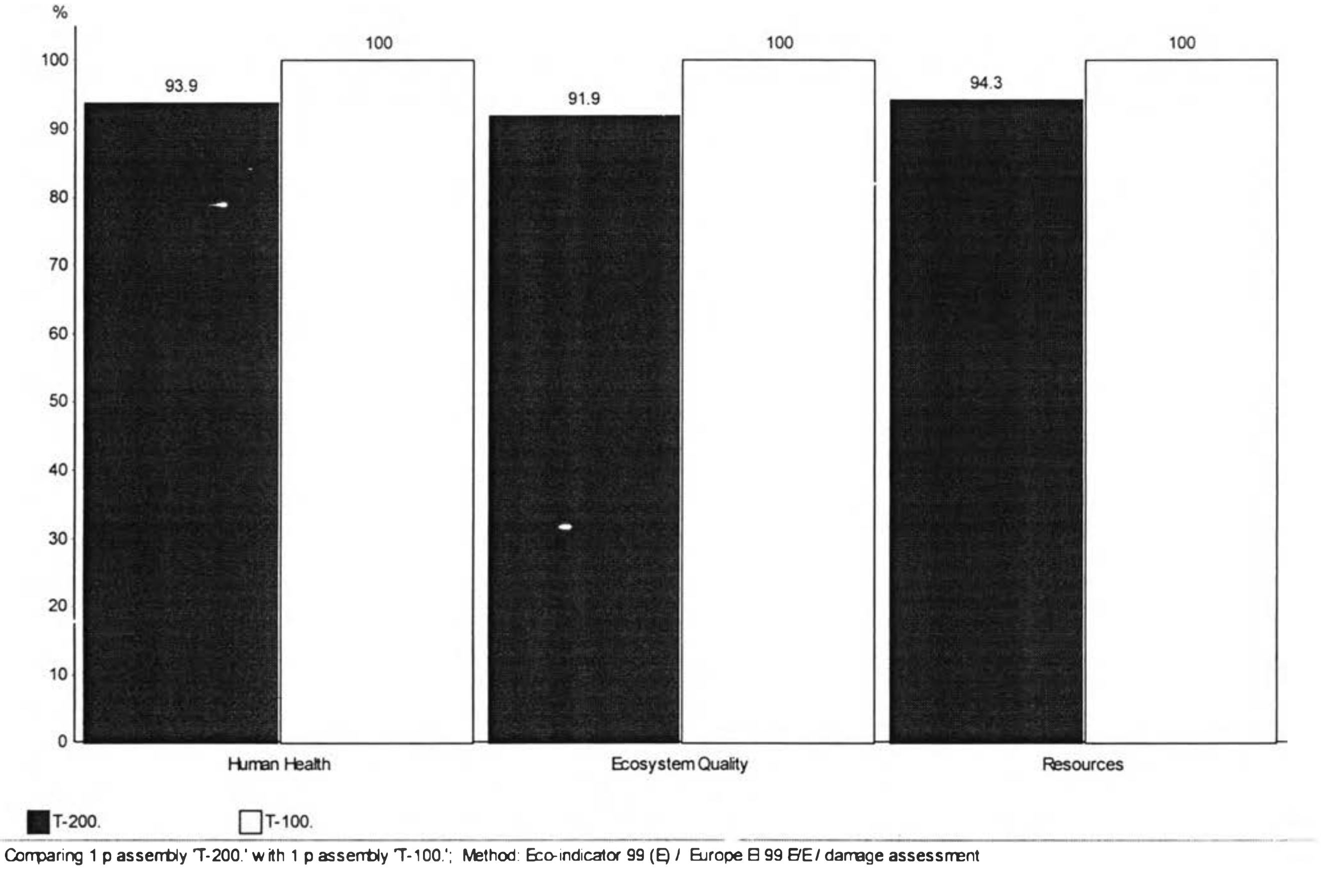


Figure 4.25 The comparison of the total amount of environmental impact between T-100 and T-200 chips by Eco-indicator 99.

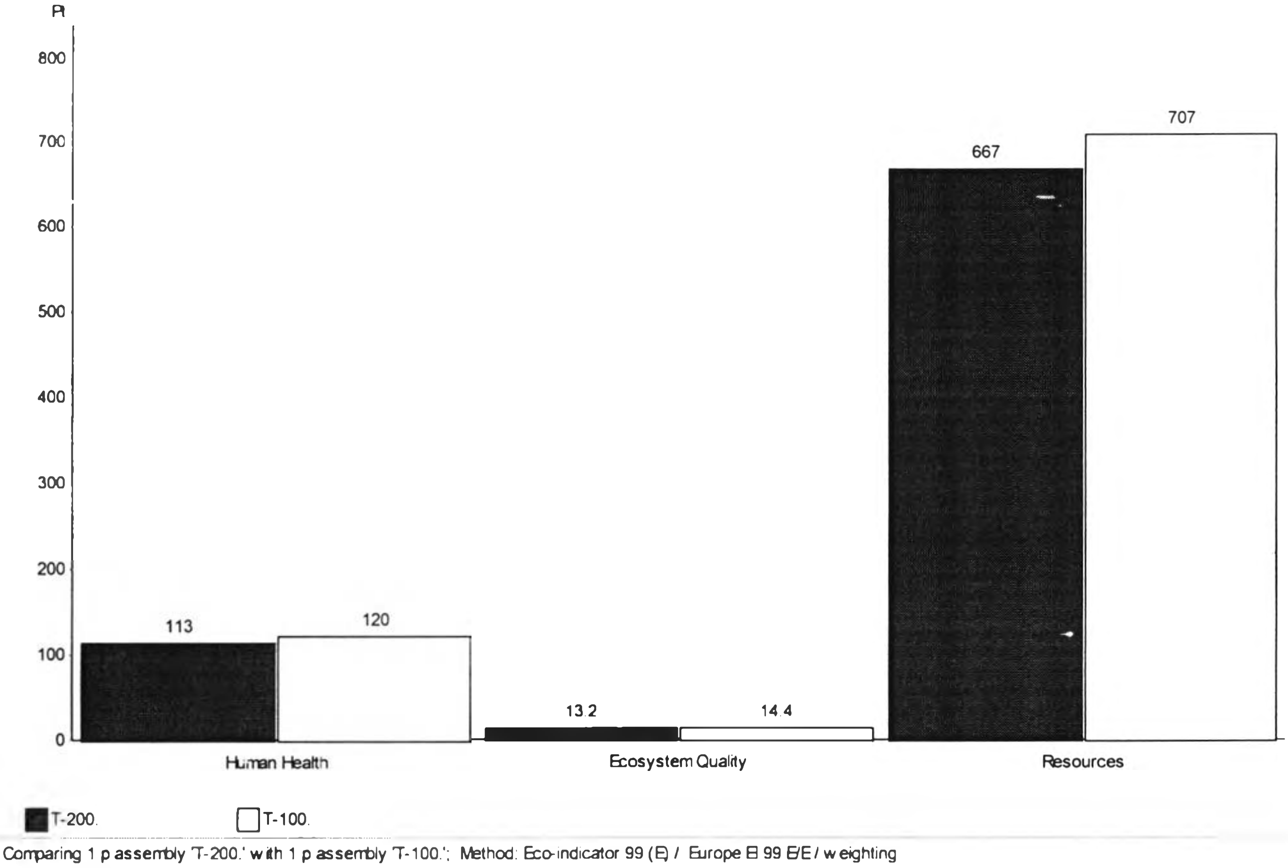
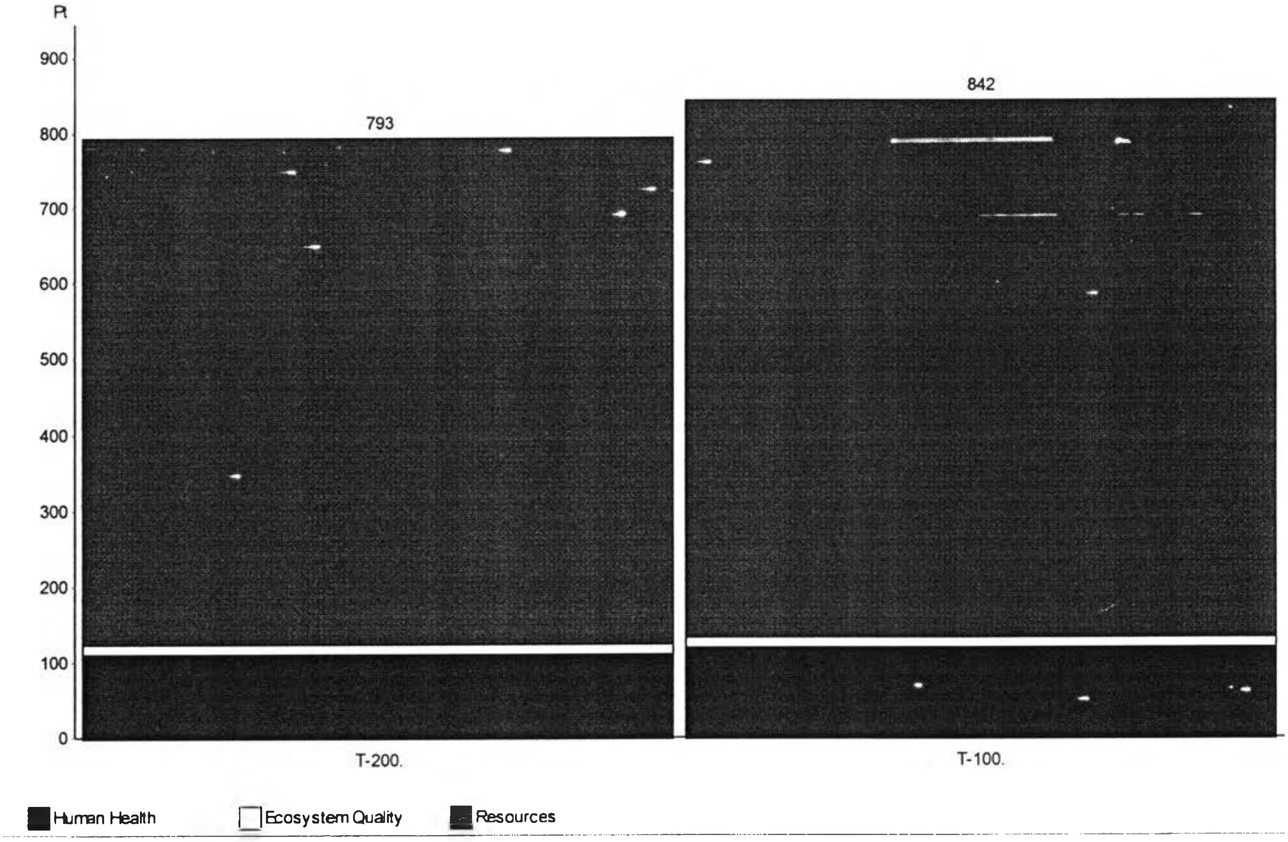


Figure 4.26 The final weight scores of T-100 and T-200 chips.



Comparing 1 p assembly 'T-200.' with 1 p assembly 'T-100.'; Method: Eco-indicator 99 (E) / Europe EI 99 E/E / single score

Figure 4.27 The comparison of the final weight score between T-100 and T-200 chips.

Table 4.1 Transportation of raw material and distance

Raw material	By	Distance
Melted Caprolactam	Truck 20 ton	200 km.
Flake Caprolactam	Sea Ship 256 ton	4807 km.

Table 4.2 Electricity that used in each process.

Process	T-100 (kw./hr.)	T-200 (kw./hr.)
Lactam preparation + Polymerization	81.5	175.6
Extraction	22.1	22.1
Dying	29.6	29.6
Water waste	35.4	35.4
Melting	120	120
Depolymerization + Condensation	122.2	122.2
Mixing	16.5	16.5

Basis : Production capacity of Polyamide chip code T-100 = 9.23 hr./1 ton
Production capacity of Polyamide chip code T-200 = 2 hr./1 ton

Table 4.3 The total amount of environmental impact potentials and energy use in the life cycle of one ton of T-100 chip

Impact category	Unit	Total
greenhouse	kg CO2	1.62E+04
ozone layer	kg CFC11	7.91E-05
acidification	kg SO2	27.7
eutrophication	kg PO4	2.95
heavy metals	kg Pb	0.000944
carcinogens	kg B(a)P	0.000223
energy resources	MJ LHV	2.68E+05
solid waste	kg	197

Table 4.4 The total amount of environmental impact potentials and energy use in the life cycle of one ton of T-200 chip

Impact category	Unit	Total
greenhouse	kg CO2	1.55E+04
ozone layer	kg CFC11	7.34E-05
acidification	kg SO2	25.5
eutrophication	kg PO4	2.72
heavy metals	kg Pb	0.000894
carcinogens	kg B(a)P	0.000202
energy resources	MJ LHV	2.53E+05
solid waste	kg	175

Table 4.5 The normalization and weighting factor from Eco-indicator 95 method

Impact category	Normalization factor	Weighting factor
greenhouse	0.0000742	2.5
ozone layer	1.24	100
acidification	0.00888	10
eutrophication	0.0262	5
heavy metals	17.8	5
carcinogen	106	10
energy resources	0.00000629	0
solid waste	0	0

Table 4.6 The total environmental impact of T-100 chip and T-200 chip that analyzed by Eco-indicator 99 method

Impact category	Unit	T-100	T-200
carcinogen	DALY	9.94E-06	8.80E-06
respiratory organics	DALY	1.54E-05	1.39E-05
respiratory inorganics	DALY	0.00277	0.00254
climate change	DALY	0.0034	0.00325
radiation	DALY	1.32E-07	1.16E-07
ozone layer	DALY	7.15E-08	6.59E-08
ecotoxicity	PAF*m2yr	26.8	23.5
acidification/eutrophication	PDF*m2yr	142	131
land use	PDF*m2yr	3.01	2.58
minerals	MJ surplus	10.6	9.21
fossil fuel	MJ surplus	2.10E+04	1.98E+04

Table 4.7 Percent contributions to the impact from each phase of T-100 chip.

Impact category	Unit	Total	Transport.	Raw mat.	Product.	Recov.	Aux.
Carcinogens	%	100	19.9	x	55.8	0.103	24.2
Respiratory organics	%	100	1.71	23.7	69.7	0.0252	4.91
Respiratory inorganics	%	100	2.13	78.6	14.9	0.185	4.17
Climate change	%	100	0.228	93.1	4.44	0.0512	2.14
Radiation	%	100	x	x	100	0.0304	x
Ozone layer	%	100	45.8	x	53.6	0.0165	0.673
Ecotoxicity	%	100	18.6	x	22.9	0.132	58.3
Acidification/ Eutrophication	%	100	2.39	81.1	12	0.173	4.32
Land use	%	100	x	x	56.4	0.116	43.5
Minerals	%	100	x	x	99.4	0.0549	0.5
Fossil fuels	%	100	0.192	87.3	9.61	0.0857	2.84

Table 4.8 Percent contributions to the impact from each phase of T-200 chip.

Impact category	Unit	Total	Transport.	Raw mat.	Product.	Recov.	Aux.
Carcinogens	%	100	21.9	x	54	0.102	24
Respiratory organics	%	100	1.85	25.6	67.7	0.0246	4.77
Respiratory inorganics	%	100	2.26	83.4	10.2	0.176	3.98
Climate change	%	100	0.232	94.8	2.95	0.0469	1.96
Radiation	%	100	x	x	100	0.0304	x
Ozone layer	%	100	48.3	x	51.1	0.0156	0.639
Ecotoxicity	%	100	20.7	x	20.7	0.133	58.4
Acidification/ Eutrophication	%	100	2.53	85.7	7.51	0.165	4.1
Land use	%	100	x	x	55.5	0.118	44.4
Minerals	%	100	x	x	99.4	0.0555	0.506
Fossil fuels	%	100	0.198	90.1	6.97	0.0796	2.64

Table 4.9 The normalization and weighting factor from Eco-indicator 99 method

Damage category	Normalization factor	Weighting factor
Human health	64.7	300
Ecosystem quality	1.95E-04	500
Resouces	1.68E-04	200

Table 4.10 Percent contributions to three impacts from life cycle of two types of chip

Damage category	Unit	T-100 compare.	T-200 compare.
Total	%	100	100
Human Health	%	14.3	14.2
Ecosystem Quality	%	1.71	1.67
Resources	%	84	84.1