CHAPTER II

LITERATURE REVIEW

2.1 Fluorescent lamp

2.1.1 Definition of fluorescent lamp

Lamp, under the Universal Waste Regulation, is defined as "the bulb or tube portion of an electric lighting device, specifically designed to produce radiant energy, most often in the ultraviolet, visible, and infra-red regions of the electromagnetic spectrum" (US.EPA, 2002).

The National Electric Manufacturers Association (NEMA) defined the fluorescent lamp as "a low pressure mercury electric-discharge, straight-shaped source, in which a fluorescing coating transforms some of the ultraviolet energy generated by the mercury is discharged into light" (NEMA, 1998). And Chastain (2003) defined the fluorescent lamp as "a discharge lamp of the low-pressure mercury type in which most of the light is emitted by a layer of fluorescent material exited by the ultraviolet radiation from the discharge".

Fluorescent lamp is also defined as a type of electric lamp that excites argon and mercury vapor to create luminescence (Wales, 2001), and a linear fluorescent lamp is an electric discharge lamp that generates light from a phosphor-coated tube (International Finance Corporation, 2001).

Types of fluorescent lamps are classified by their shapes, length, wattage, diameter, or usage. Usually, fluorescent lamps are a 4-foot or 8-foot long straight, circular, or u-shape tube and the tube diameter is 1, 1.5, or 2.125-inches (Davis, 2001). Each lamp tube is identified by a code containing information such as F##T##. The letter "F" in the code stands for fluorescent and the first number indicates the power in watts (or strangely, length in inches in very long bulbs), while the letter "T" indicates that the shape of the lamp is tubular, and the following number is the diameter in eighths of an inch. For example, the T8 lamp is a tubular lamp which has a diameter of 1 inch and the T12 lamp is a 1.5 inch diameter lamp (Wales, 2001).

2.1.2 Composition of fluorescent lamp

A typical fluorescent lamp consists of a glass tube sealed with argon or another inert gas and mercury vapor, phosphor powder coats the inside the tube surface, a tungsten coil forming electrodes at each end of the tube coated with an electron emitting substance, two end caps are made of aluminum and other metals (Battye, 1994), and there is a minute amount of elemental mercury (Davis, 2001, Dang et al., 2002; Korista, 2004). The composition of a fluorescent lamp is shown in Figure 2.1
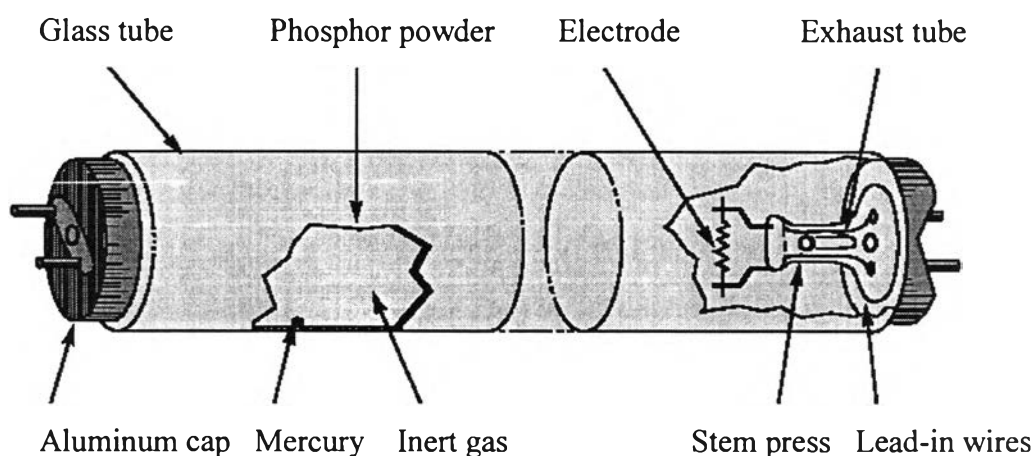
Figure 2.1 Composition of a fluorescent lamp

Source: http:/ecom.mysylvania.com

The composition ratio of a fluorescent lamp is a trade secret and based on technical know-how of each manufacturer. The lamp composition of one of the manufactures in Thailand is shown in Table 2.1 (PCD, 2004)

Table 2.1 Composition of a fluorescent lamp

Number	composition	%Mass
1	Glass tube	89.79
2	Phosphor powder	1.39
3	Aluminum cap	0.93
4	Fiber insulator	0.12
5	Contact pin (Brass)	0.58
6	Cement	1.46
7	Electrode (Tungsten)	0.01
8	Oxide	0.01
9	Exhaust tube	3.1
10	Flare	2.41
11	Weld (Nickel and Copper)	0.2
Total		100.00

Remark: each lamp contains about 10 mg of mercury

The glass used in the fluorescent lamp is of the soda lime type. The typical chemical composition of glass contains SiO_2, Al_2O_3, CaO, MgO, Na_2O, K_2O, and B_2O_3 (Parkinson, 2002). The percentage of each component is shown in Table 2.2

Table 2.2 Typical chemical composition of glass

Chemical constituent	%
SiO_2	72.5
Al_2O_3	2.6
CaO	5.7
MgO	2.9
Na_2O	14.6
K_2O	1.2
B_2O_3	0.3

Source: www.britglass.co.uk

The gas that fills in the fluorescent lamp tube is usually argon, an inert gas, to prevent the burning of the tungsten coil when oxygen is present. Krypton gas is also used in some premium light bulbs since its atom is more massive than an argon atom and krypton is more effective in bouncing tungsten atoms back toward the filament than argon after tungsten sublime (Korista, 2004).

Phosphor powder is an important component in fluorescent lamps; its function is to convert ultraviolet radiation to visible light. The powder is composed of various phosphor compounds (Battye, 1994). The main compound is calcium phosphate in its crystalline phase, $Ca_5(PO_4)_3F$-fluorapatite. Other minor phases are $CaCO_3$-calcite, $CaHPO_4$-monetite, $CaHPO_4 \cdot 2H_2O$-brushite, TiO_2-rutile/anatase, and β-$Ca_3(PO_4)_2$-whitlockite. The exact chemical composition of phosphor powder depends on the color type of the lamp. The approximated chemical composition of phosphor powder in a 40-watt standard fluorescent lamp is shown in Table 2.3 (Raposo, 2003).

**Table 2.3** Approximated chemical composition of phosphor powder

Element	Mass%	Element	µg/g	Element	µg/g
Ca	37.91±0.11	Al	580±30	Co	4±1
P	18.12±0.36	Ba	310±15	La	35±4
F	2.95±0.14	Mg	143±2	Nd	31±3
Mn	0.86±0.02	Sr	125±7	Ce	12±1
Cl	0.72±0.04	Ni	90±4	Sm	6±0.3
Sb	0.61±0.01	Pb	38±3	Dy	3±0.3
Fe	0.19±0.01	Cr	10±1	Er	3±0.3
Cd	0.18±0.01	Zn	7±1	Ho	2±0.3

The tungsten electrode is commonly coated with alkali metal carbonates ($BaCO_3$, $CaCO_3$, and $SrCO_3$), a thermionic emitter, and the tin oxide (SnO_2). These substances are used to generate electrons when electrical energy is employed. The carbonate compounds are decomposed into metals and metal oxides during lamp manufacturing (Dang et al., 2002)

Mercury is a vital component for the functioning of fluorescent lamps. It, in vapor form, emits ultraviolet (UV) light when struck by an electron. The amount of mercury in the lamps varies, depending on type of lamp, manufacturers as well as the year of manufacturing (Battye, 1994; Raposo, 2003).

2.1.3 Fluorescent lamp operation

Fluorescent lamps provide visible light by passing an electric arc through mercury vapor in the lamps (Wilson, 1997). The fluorescent bulbs start their operation when a voltage is applied. Electrons from electron emitting substances move through the tube from one electrode to the other, striking inert gas atoms. The atoms emit more electrons and these electrons strike mercury vapor atoms. The attacks energize the atoms of mercury causing them to emit ultraviolet (UV) light (Battye, 1994). The UV light is absorbed by phosphor powder coated inside the tube. Finally, the phosphor re-radiates the energy in the form of visible light (Wales, 2001). Figure 2.2 shows a the schematic drawing of fluorescent lamp operation.
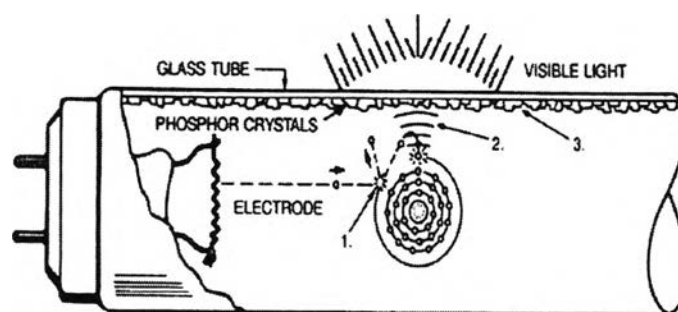
Figure 2.2 Schematic drawing of fluorescent lamp operation

Source: http://www.buildinggreen.com/auth/article.cfm

2.2 Hazardous waste

2.2.1 Definition of hazardous waste

The definition of hazardous waste is not mentioned under any regulations of Thailand. However, the term hazardous substance is explained in the Enhancement and Conservation of National Environmental Quality Acts, B.E 2535 and the Hazardous Substance Act, B.E. 2535. A hazardous substance includes the following:

(1) Explosives.

(2) Flammable Substance.

(3) Oxidizing agent and peroxide.

(4) Toxic substance.

(5) Substance causing diseases.

(6) Radioactive substance.

(7) Mutant causing substance.

(8) Corrosive substance.

(9) Irritating substance.

(10) Other substance either chemicals or otherwise which may cause injury to the persons, animals, plants, property, or environments.

In the U.S., , the term hazardous waste, under the Resource Conservation and Recovery Act (RCRA), is defined as "a solid waste or combination of solid wastes, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may;

(A) cause or significantly contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness; or

(B) pose a substantial present or potential hazard to human health or disposed of otherwise managed."

Hazardous wastes, according to The Office of National Environmental Board (ONEB), is defined in 1992 as: "substances and materials which are not used or cannot be used, which contain or are contaminated with combustible substances, corrosive substances, highly active substances, explosives, toxic substances, soluble substance, radio-active substances, and/or disease producing organisms which are produced by various industrial, community, agricultural actives". And in 1989 as: "any waste or combination of wastes, which, because of its quality, concentration, or

infectious characteristic, may cause or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness; or pose a substantial present or potential hazard to human health or disposed of otherwise managed".

Hazardous waste can also be defined as "waste (solids, sludges, liquids, and containerized gases) other than radioactive and infectious waste which, by reason of their chemical activity or toxic, explosive, corrosive, or other characteristics, cause danger or likely will cause danger to health or the environment, whether alone or when coming into contact with other waste" (LaGrega ,al, et., 2001).

2.2.2 Hazardous waste identification

Each country has its own definition of hazardous waste. As a result, there are both similar and different criteria to identify and classify hazardous waste among these countries. In Thailand, according to the Notification of the Ministry of Industry No.6 B.E. 2540 (1997), hazardous wastes are classified into 4 sections as follows:

1. Ignitable, corrosive, reactive, toxic and leachable substances.

2. Wastes from non-specific and specific sources.

3. Discarded commercial chemical products, off-specification species, container residues, and spill residues.

4. Chemical wastes.

The two main criteria used to identify whether any waste is hazardous are its characteristic and listing (PCD, 2004). Hazardous wastes can be divided into 7 groups based on their characteristics of properties:

1. Ignitable substances: substances which have flash point less than 60 degrees Celsius, cause fire through fiction, absorb moisture or react by themselves, are ignitable compressed gases or oxidizers.

2. Corrosive substances: substances which have pH equal to or less than 2 and pH equal to or more than 12.5, corrode steel of the class of SAE 1020 at a rate higher than 6.35 millimeters per year at a temperature of 55 degrees Celsius.

3. Reactive substances: substances which are unstable, react quickly and violently with water, yield an explosive mixture or generate toxic gases when combined with water, or generate a toxic gas when it consist of cyanide or sulfide at a pH between 2 to 11.5.

4. Toxic substances: substances which cause human death in only a small quantity, is toxic to experimental animals or carcinogen, have heavy metal content in excess of standard values when extracted.

5. Leachable substances: substances which, when extracted using the leachate extraction procedure specified in the notification of the Ministry of Industry No.6 B.E.2540 (1997), have heavy metal or toxic materials content in the extraction fluid equal to or more than standard values.

6. Pathogenic substances: substances which are contaminated with pathogen in the amount or concentration that causes disease or infection.

7. Radioactive substances: substances which consist of or are contaminated with unusable radioactive substance in excess of the nature level, causing contamination during production.

Lists to identify hazardous waste in Thailand are as follows:

1. List of chemical wastes attached to the Notification of the Ministry of Industry No.2 B.E.2543 (2000)

2. List of wastes or unusable materials attached to the Notification of the Ministry of Industry No.6 B.E.2540 (1997)

In the United State, hazardous wastes as define by RCRA are also classified into two classes: characteristic wastes and listed wastes (Davis, 1998 and Tang, 2004). The first class is defined by the properties as follows:

1. Ignitability, which is decided by the flash point of the chemical.

2. Corrosivity, which corrodes when pH of the waste is less than 2 or greater than 12.5.

3. Reactivity, which is determined by the capability of the waste to quickly change its state.

4. Toxicity, which is determined by the leaching procedure (TCLP).

A listed waste is any waste which contains a chemical that is catalogued by the EPA as hazardous. This class of waste has been listed based on several factors such as

toxicity, persistence and degradability in nature, potential for bio-accumulation, including flammability, corrosiveness and other hazard properties (Tang, 2004). These wastes are spent halogenated and non-halogenated solvents, electroplating baths, wastewater treatment sludges from many production processes, wastes from various distillation processes, and some discarded chemical products such as acutely hazardous wastes (arsenic acid, cyanides, pesticides, etc.) and toxic wastes (benzene, creosote, phenols, toluene, etc.) (Davis, 1998). The listed wastes are grouped into four categories:

1. Wastes from non-specific sources. The EPA hazardous waste number of these wastes starts with F.

2. Wastes from specific sources. The EPA hazardous waste number of these wastes starts with K.

3. Substances identified as acute hazardous wastes that are discarded commercial chemical products, off-specification species, containers residues, and spill residues. The EPA hazardous waste number of these wastes starts with P.

4. Substances identified as hazardous wastes that are discarded commercial chemical products, off-specification species, containers residues, and spill residues. The EPA hazardous waste number of these wastes starts with U.

2.2.3 Fluorescent lamp identification

A discarded fluorescent lamp has been considered as a hazardous waste under RCRA since 1990 if it exhibits the toxicity characteristic. The toxicity characteristic of the fluorescent lamp is determined by the toxicity characteristic leaching procedure (TCLP). When employing TCLP, if the mercury concentration is equal to or greater than 0.2 mg/L, the fluorescent lamp is defined as a hazardous waste (Babb, 1994 and Bullough, 2000). Under this regulation, the lamps that fail the TCLP are strictly controlled with requirement for the storage, packing, labeling, transportation, and disposal. In 1994, the EPA reconsidered the classification of fluorescent lamps in order to reduce the number of the fluorescent lamps in disposal facilities and increase the number of lamps in recycling facilities. By 2000, the EPA regulated the fluorescent lamp as an universal waste, a subset of hazardous waste (Daly, 2000).

In Thailand, fluorescent lamps are also defined as hazardous waste, since they have mercury as their constituent following article 22, section 4 of the Notification of the Ministry of Industry No.6 B.E.2540 (1997) (Ministry of Industry, 1997).

2.3 Mercury

2.3.1 Properties of mercury

Mercury, Hg, is classified as a metallic element. It is the only metal which is a silvery-white liquid at room temperature. In Latin, It is called "Hydrargyrum" that refers to liquid silver. Its atomic number is 80 and its atomic weight is 200.59. Mercury has a freezing point and boiling point of -38.9 °C and 356.58 °C respectively. Mercury is also volatile at room temperature, its vapor pressure is 12 μmHg and its density is 13.54562 g/cm^3 at 20 °C. The concentration of the saturated vapor of mercury at standard temperature and pressure (25 °C, 1 atm) is 13 mg/m^3 (Calvert, 2004).

Mercury is associated with zinc (Zn) and cadmium (Cd) in the same column of the periodic table. Mercury has two valence electrons in s-orbits, and display valance+1 and +2, but Zn and Cd show only +2. Its electrochemical potential is less than hydrogen, so it does not displace hydrogen, and does not corrode in air (Calvert, 2004).

Elemental mercury vapor is colorless and relatively insoluble. Nevertheless, small quantities of mercury vapor dissolved in water and other solvents are considered as a serious problem. Mercury solubility in air-free water is approximately 20 μg/liter at room temperature. In the presence of oxygen, metallic mercury is rapidly oxidized to the ionic form-mercury (I) and may obtain a concentration in water as high as 40 μg/liter (WHO, 1976).

Mercury compounds are classified into two major classes: organic and inorganic mercury compounds. Inorganic mercury compounds contain the metallic forms, the salts of mercury (I) and mercury (II) ions, and complex forms in which the mercury (II) ion is reversibly bound to such tissue ligands as thiol groups and protein. Organic mercury compounds are compounds in which mercury is directly linked , by a covalent bond, to a carbon atom (WHO, 1976).

Mercurous (I) chloride (Hg_2Cl_2) or Calomel is the well-known mercury salt. It was broadly used as a component in teething powders and in anthelmintic preparations in the first half of this century. It is a low toxic compound of mercury because of its very low solubility in water. Although mercury (I) forms few complexes with biological molecules, in the presence of protein and other molecules containing SH groups, it gives one atom of metallic mercury and mercury (II) ion which forms complexes with halide, thiol, and other groups (WHO, 1976).

Mercuric (II) chloride ($HgCl_2$) or corrosive sublimate is a highly reactive compound, soluble and very toxic. It rapidly denatures proteins and it is used as an antiseptic in an 0.1% solution and was widely used in the past as a disinfectant. It forms four different complexes with chloride such as $HgCl^+$, $HgCl_2$, $HgCl_3^-$ and $HgCl_4^=$ when it is soluble in water and solution (WHO, 1976).

Mercuric oxide (HgO) is in two forms. The first is a bright- red crystalline powder, this is attained from heating the metal in air or by calcining the nitrate. Another form is obtained as an orange-yellow powder by precipitating a solution of a mercuric salt with potash. The yellow form is the most reactive and changed to red when heated to 400 ^{O}C. When the red oxide is heated up to 630 ^{O}C, it becomes black and decomposes into mercury and oxygen respectively. It slightly dissolves in water, to which it imparts an alkaline reaction and strongly metallic taste (LoveToKnow, corp., 2004).

Mercuric sulphide (HgS), called cinnabar, is one of the most important mercury compounds. It occurs in nature as an ore and is widely used as a pigment. It is a black powder obtained by triturating mercury with sulphur and also by precipitating a mercuric salt with sulphuretted hydrogen. It reacts with nitric acid improperly and dissolves in potassium sulphide solutions to form double salts of variable composition (LoveToKnow, corp., 2004).

In addition to simple salts, such as chloride and nitrate, mercury (II) forms an important group of organometallic compounds. Mercury attaches to either one or two carbon atoms to form the RHgX and RHgR' compounds where R and R' represent the organic moiety. A large number of these compounds are in the type RHgX where X is a hydroxyl (OH) or a cyano (CN) or possibly a halogen atom. The carbon-mercury

bond is chemically stable. It is neither soluble in water nor by weak acids or bases. The organic moiety, R, is the alkyl, the phenyl, or the methoxyethyl radicals. From a toxicological point of view, the most important of these compounds is the subclass of short-chain alkylmercurials in which mercury is linked to the carbon atom of a methyl,ethyl, or propyl group (WHO,1976)

Dimethyl mercury ($Hg(CH_3)_2$), an extremely toxic material, is a colorless, sweet smelling liquid, and very slightly soluble in water. It is an ignitable substance, with a flash point of -4 °C. This compound rapidly penetrates the skin resulting in severe exposure, which causes death (Kuckuck, 2001).

In environments, mercury can move or fluxe between various media such as water, soil, and air. The quantities of mercury in these media are often called pools. Since elemental mercury, Hg^o,can volatilize relatively easily, it emits itself into the atmosphere. Atmospheric transport is the important mechanism by which Hg^o is dispersed throughout environments. Mercury can be released to the atmosphere as a gas or bound to particles until deposition. This process results in the deposition of mercury far from its source. In addition, mercury can also be transported by a water stream system and sediment. The distance of mercury movement in a water resource may be long or short, and is limited by sedimentation if mercury is carried on particles. In environmental pathways, mercury can be transformed to various forms. Oxidation-reduction and methylation-demethylation are two main reactions that convert forms of mercury. In oxidation-reduction reactions, a form of mercury is either transformed to a higher valence state or a lower valence state. In a methylation reaction, mercury, the oxidized or mercuric species (Hg^{2+}), is transformed into methylmercury when bonded with a methyl group (CH_3). In the methylation process, the microorganisms, particularly methanogenic and sulfate-dependent bacteria, are considered to affect the conversion of Hg^{2+} to methylmercury under an anaerobic condition such as in wetlands and river sediments. This reaction occurs mainly in aquatic, low pH (acidic) environments with high concentrations of organic matter. Methylmercury is an extremely toxic form of a mercury organic compound and has the ability to migrate through cell membranes. This substance builds up in living tissues (bioaccumulation) and increases in concentration up the food chain (biomagnification), from plankton, to

fish, to fish eating species like otters and loons, and human (Environmental Canada, 2004)

2.3.2 Mercury poisoning

All forms of mercury are toxic. However, each form has differs in how it diffuses through the body, the clinical signs and symptoms and its response to treatment modalities. Inhalation, ingestion, injection, and absorption through the skin result in mercury poisoning.

At room temperature, elemental mercury is in liquid form and in vapor form; in these forms it can easily pass through the respiratory system into the blood stream and red blood cells. Once it gets in the body, elemental mercury is mostly transformed to its mercury (II) form by catalase in the erythrocytes, where it is ionized and trapped, ascribing to its significant toxic effect (Iowa Department of Public Health [IDPH], 2004). In experimental animals such as rabbits, mercury vapor can harm the kidneys, liver, brain, heart, lungs and colon. Exposure to mercury vapor at a concentration of 28.2 mg/m^3 for 4 hours caused damage to the important organs of rabbits. For humans, mercury vapor can affect the central and peripheral nervous systems, lung, kidneys, skin, and eyes. Like in animals, mercury vapor is also mutagenic and affects the immune system in humans. Acute exposure to high concentrations of mercury vapor can cause the chills, nausea, general malaise, tightness in the chest, chest pains, dyspnea, cough, stomatitis, gingivitis, salivation, and diarrhea. Chronic exposure to mercury vapor results in weakness, fatique, anorexia, weight loss, and disturbance of gastrointestinal function. A tremor may appear starting with the fingers, eyelids, and lips which may develop to generalize trembling of the entire body and violet chronic spasms of the extremities. Behavioral and personality changes may occur along with the development of the tremors (OSHA, 2004).

Inorganic mercury, found mostly in salt forms, enters the body by ingestion and absorption through the skin. It accumulates mainly in the kidneys resulting in significant renal failure. The low solubility in lipid limits its penetration into the nervous system, but the slow elimination and chronic exposure, significantly, result in mercuric ion accumulation in the central nervous system and subsequent toxicity. Dermal exposure to inorganic mercury for along period of time may also lead to

toxicity. The acute signs and symptoms of inorganic mercury can include ashen-gray mucous membranes, hematochezia, vomiting, severe abdominal pain, and hypovolemic shock. The systemic effects such as metallic taste, stomatitis, gingival irritation, foul breath, the loosening of teeth, and renal tubular necrosis usually occur several hours after ingestion and may last several days (OSHA, 2004).

Organic mercury is found in three forms: aryl and short and long chain alkyl compounds. They are absorbed more perfectly in the gastrointestinal tract than organic salts. Once absorbed, the aryl and the long chain alkyl forms are transformed to their organic forms and exhibit toxicity like inorganic mercury. Unlike the aryl and the long chain alkyl compounds, the short chain alkyl mercurials are easily absorbed in the gastrointestinal tract and are stable in their initial forms. Because of its high lipid solubility, alkyl organic mercury is distributed identically throughout the body, accumulating in the brain, kidneys, liver, hair, and skin. These compounds also cross the blood brain barrier, and placenta, and penetrate erythrocytes, attributing to neurological symptoms, teratogenic effects, and high blood-to- plasma ratio(IDPH, 2004).

Minamata disease is a methylmercury poisoning disease that affects the nervous system, mainly the central nervous system. Minamata disease comes from the name of a bay in Japan named "Minamata" where the people had set of nervous symptoms after they consumed large quantities of fish and shellfish in this bay (UNEP, 2005). The main signs and symptoms are sensory disturbance in the distal portions of four extremities, cerebellar atoxia, bilateral concentric contraction of the visual field, disturbed ocular movement caused by an affected central nervous system (CNS), impairment of hearing caused by CNS, and equilibrium disturbance caused by CNS (Ministry of the Environment, 2002). In addition, congenital systems can occur when the mother consumes seafood contaminated with methylmercury. The patients were born with a condition resembling cerebral palsy, caused by methylmercury poisoning of the fetus via the placenta (UNEP, 2005). This disease differs from inorganic mercury poisoning which mainly damage kidneys and other important organs, however it is not confirmed whether it damages other organs aside from those in the system.

To protect the health and safety of workers, several agencies have established standards for mercury. The Occupational Safety and Health Administration (OSHA) has set up the permissible exposure limit (PEL) of 0.1 mg/m^3 of air as a ceiling limit for mercury vapor. The National Institute for Occupational Safety and Health (NIOSH) also has recommended a exposure limit for mercury vapor of 0.05 mg/m^3 as a time weight average (TWA) for up to a 10-hour workday and a 40-hour workweek. Another agency, the American Conference of Governmental Industrial Hygienists (ACGIH), has assigned a threshold limit value (TLV) of 0.025 mg/m^3 as a TWA for a 8-hour workday and a 40-hour workweek (OSHA, 2004). In Thailand, the Ministry of Interior also has established the standard for mercury vapor in the workplace. According to the Notification of Ministry of Interior, issued under the Announcement of the Revolutionary Party No.103 B.E.2520 (1977), The allowable concentration of mercury is 0.05 mg/m^3 of air (Ministry of Interior, 1977, cite in Secot Co., Ltd, 2003).

The Occupational Safety & Health Administration (OSHA, 1991) and The National Institute for Occupational Safety and Health (NIOSH, 1994) generated the information of mercury vapor sampling in the workplace atmosphere following the OSHA's method ID-140 and the NIOSH's method 6009, respectively. Solid sorbents, e.g. active sampler were recommended to sample mercury vapor. The active sampler sampled mercury vapor in the workplace into the sorbent tube by using a calibrated sampling pump. And the samples were prepared and then analyzed by cold vapor atomic absorption spectrophotometer. In addition, the direct reading instruments were also used to detect elemental mercury vapor. For instance, the Jerome M-411 gold film mercury vapor was used to determine mercury vapor emissions from the dental amalgam (Neme et al, 1999) and the fluorescent lamps (Aucott et al, 2003). And the Trekran mercury analyzer model 2537A was employed to measure mercury from mercury – containing waste in waste storage containers (Lindberg et al, 1999) and from materials containing mercury in the residences (Carpi and Chen, 2001).

2.3.3 Mercury in the fluorescent lamps

Mercury is an important element of fluorescent light bulbs. During lamp production, it is inserted into the lamp mainly in liquid form, and with its vapor pressure, a small portion of mercury turns into vapor. In the vapor phase, mercury converts electrical energy to the UV light which subsequently is transformed to visible light (Battye, 1994).

The amount of mercury placed in a fluorescent lamp depends on the type of the lamp, the year of production, and also the manufacturer (Battye, 1994; Raposo, 2003). The total mercury content for T12 and T8 lamps as a function of year of manufacture and lamp types provided by manufacturers is showed in Table 2.4 (US.EPA, 1998).

Table 2.4 Total mercury content of T12 and T8 lamps

Year of manufacture	Mercury content (mg/lamp)	
	T12 lamp	**T8 lamp**
Pre-1992	41	30
1992-1996	30	15
1997-2007	21	10

The mercury content in fluorescent lamps produced prior to 1992 is more than 40 and 30 mg in a T12 and a T8 lamp. Manufacturers estimated that between 1997 and 2007 the total mercury content in T12 and T8 lamp will be less than 21 and 10 mg, respectively. And information indicated by manufacturers showed that the mercurycontent of fluorescent lamps will continue to be reduced in the future (US.EPA,1998).

Mercury contained in used fluorescent lamps is in several forms and several parts of the lamp. The National Electrical Manufacturer Association (NEMA) and Sylvania, a lamp manufacturer, indicated that mercury in the lamp is in two forms; elemental mercury as vapor phase and divalent mercury form combined with the phosphor powder (US.EPA, 1998). Elemental mercury, near the end of lamp life, might exist in vapor form and liquid form as small particles or beads (Aucott et al,

2003). It was estimated that the amount of vapor phase mercury contained in a fluorescent lamp was 0.04 mg (NEMA, 2000). In contrast, Aucott et al, 2003 estimated that about 0.018 mg of mercury in vapor form is contained in the lamp. However, a recent study showed that only 2.9 μg of mercury in the T12 lamp was in vapor phase (Jang et al, 2004). In phosphor powder, mercury species studied by thermo-desorption/atomic absorption spectrometry (TDAAS) are Hg^o, Hg^{+1}, and Hg^{+2}, while Hg^o and Hg^{+1} are more dominant than Hg^{+2} as presented in US.EPA's report (Raposo, 2003). For glass matrix, Dang et al, (1999) suggested that mercury in Hg^o is the dominant species which reacts with the Na in the glass. In contrast, Doughty et al, (1995) and Raposo et al, (2003) postulated that oxidized species, i.e., Hg^{+1}, and Hg^{+2} were predominant upon the metallic species (Hg^o) in the glass metric.

2.3.4 Mercury released from fluorescent lamps

Mercury released into environments comes from natural and anthropogenic sources. The human activities generating mercury are fossil fuel combustion in industrial processes including coal-fired plants, waste incineration, and the disposal of mercury containing waste such as used fluorescent lamps (Dunmire et al, 2003). In the U.S., it is estimated that mercury emitted from anthropogenic sources is approximately 158 tons, about 87% of these emission results from various types of combustion such as coal combustion, and incineration. Approximately 14% comes from the small activities including the manufacturing processes for cement and chlor-alkali. About 1.5 tons or 1% of total released mercury from anthropogenic sources is emitted from lamp breakage (US.EPA., 1997).

The Research Triangle Institute, under contact to the EPA, estimated the mercury emissions from lamp breakage. It was estimated that, overall, about 6.8 percent of the total mercury content per lamp was released after lamp breakage (Truesdale, 1993, cited in US.EPA, 1998). The National Electric Manufacturers Association estimated mercury released from lamp disposal in the USA, it was estimated that vapor phase mercury in 4-ft fluorescent lamps was 0.3 percent of the mercury contained in a lamp and this amount of mercury vapor was released when the lamp was broken (NEMA, 2000). Tetra Tech Inc. also studied mercury emission from broken lamp. It was found that about 3 percent of the total mercury is emitted over a

20-day period after lamp breakage (Tetra Tech Inc., 1994, cited in US.EPA, 1998). Based on the studies of the Research Triangle Institute in 1993 and the National Electric Manufacturers Association in 1995, the US.EPA. estimated the amount of mercury vapor emitted from a broken lamp ranged from 1.2 to 6.8 percent of the total mercury (US.EPA., 1998). Lindberg et al. (1999) studied mercury released in municipal solid waste disposal. They indicated that about 20 to 80 percent of the total mercury volatilized from a broken lamp over a week. In contrast, Aucott et al.(2003) studied the release of mercury from broken fluorescent bulbs. With the assumption that all mercury released was elemental vapor, it was found that between 17 and 40% of the mercury in broken low-mercury fluorescent bulbs was released to the air during a two-week period immediately following breakage. One-third of the mercury release occurred during the first 8 hours after breakage. And a typical discard lamp released between 3 and 8 mg of elemental mercury vapor over two weeks.

2.4 Used fluorescent lamp management

2.4.1 Used fluorescent lamp waste stream

The lifetime of each lamp varies, depending on the type of the lamp, technologies of each manufacturer, the usage of consumers, etc. In general, a fluorescent lamp has a lifetime of three or four years under normal use (Truesdale, 1993, cited in Battye, 1994). The fluorescent lamps are thrown away into the trash cans when they burned out. In Thailand, the number of the used fluorescent lamps discarded per year was studied by PCD. It was estimated that in Thailand, about 41 million tubes of all types of fluorescent lamps was produced in 2004. And with the assumption that the lifespan of fluorescent lamps is three years, PCD also forecasted the generation of the used fluorescent lamps in 2005 to 2007. The results are shown in Table 2.5 (PCD, 2005).

For Bangkok Metropolitan, about 36.67 tons of household hazardous waste was collected in October 2003 to July 2004. Of these wastes, there was 13.54 tons of discarded fluorescent lamps or 36.9 percent of the total waste. After collection, the lamps were transported and stored at a transfer station until sent to the private company for treatment and disposal (PCD, 2005). For other local areas, most of the

used lamps discarded from household including other Community Generated Hazardous Waste (CGHW) were collected and transported by local authorities, and disposed of in dumps or landfills (PCD, 1998). During transportation, it was assumed that all lamps in the tracks were broken if these lamps were not packed properly. And mercury contained in these lamps vaporized into the atmosphere and threatened the health of the sanitary workers (Truesdale, 1993, cited in Battye, 1994)

Table 2.5 Amount of discarded fluorescent lamps in 2005-2007

Year	Amount of discarded fluorescent lamps (thousand tubes)
2005	43,101
2006	48,771
2007	49,724

In the U.S., NEMA estimated that about 620 million lamps were discarded in 1999. 71 percent of these lamps were disposed of in landfills, 15 percent was recycled, and 14 percent was sent to incinerators (NEMA, 2000).

2.4.2 Stabilization/ Solidification of the used fluorescent lamp residue

Stabilization/ solidification (S/S) is a term that generally refers to the waste treatment processes that use binders and additives to treat waste for disposal into landfills or for other purposes. S/S is designed to improve the handling and physical characteristics of the waste, reduce the mobility and toxicity of pollutants in the waste and limit the solubility of any contaminants of the waste (Arozarena, 1989; Wile, 1998).

Stabilization is a process using reagents to minimize the rate of contaminant migration into environments, or reduce the level of toxicity. In contrast, solidification is defined as a process by which the solidifying materials are combined with a hazardous waste to make a massive material in order to increase the strength, and decrease the compressibility and the permeability of the waste (LaGrega ,al, et., 2001).

The S/S of used lamp residue was recommended by the Department of Industrial Work (DIW) following the Notification of the Department of Industrial work No.1, B.E. 2531(1988). In these processes, the lamp residue was ground into small pieces and mixed with a sodium sulfide solution. The mixture subsequently was solidified by cement before disposal into landfills (DIW, 1988). At present, this method is employed by private companies such as the General Environmental Conservation Public Co., Ltd. (GENCO) and the Professional Waste Technology (1999) Public, Co., Ltd. to treat the used fluorescent lamps mainly from factory sources. The S/S of the lamp residue was also studied; sodium sulfide and cement and lignite fly ash were used as a stabilizing agent and binders, respectively. The results showed that the stabilization efficiency of mercury was about 91.40% and 99.49% with the used sodium sulfide 1.75 and 3.00 times stoichiometric amount, respectively with a waste/binder ratio of 0.25 (Anuwat, 1996). Other materials such as silica fume were also investigated as an alternative binder. The results indicated that the optimum ratio of sodium sulfide for mercury stabilization was 1.75 times the stoichiometric amount with the stabilization efficiency of about 97.72% and 97.77% using cement mixed with silica fume and cement mixed with lignite fly ash as binders respectively. Sole cement was also used as the binder. And the maximum waste/binder ratio of 0.75 at the curing time of 7 days resulted in mercury leached from solidified waste meeting the standards set in the Notification of the Ministry of Industry No.6, B.E.2540 (1997) (Douangsamorn, 1997).

2.4.3 Fluorescent lamp crushing unit

The fluorescent lamp crushing unit or fluorescent lamp crusher is a device which crushes the used lamp to reduce the volume of the lamp for disposal in landfills, or to separate the glass and metal endcaps from phosphor powder for recycling mercury (Battye, 1994). The fluorescent lamp crushing unit was divided into two categories; the small on-site fluorescent lamp crusher and the large scale fluorescent lamp crusher (Davis, 2001).

In general, the small fluorescent lamp crushers consist of a container top-mounted crusher and a container --a drum or a bag. The difference between these units is the air pollution control system. The simple models of crushing units did not have any systems to control mercury emission while others utilized a complex system (Battye, 1994; Davis, 2001). Most of the fluorescent lamp crushing units available on the market use a filtration system to control air emissions. To capture mercury vapor, the activated carbon impregnated with sulfur or potassium iodine is applied. Some models also add a particulate bag filter and a High Efficiency Particulate Air (HEPA) filter to remove particulate matter before the activated carbon filter (Davis, 2001). However, some units use a different system to control mercury vapor. For instance, a unit from the UK employed a water spray as its air pollution control (Balcan engineering, 2000). The crushing units varied in rates of lamp feeding and the capacity to contain the crushed lamps depending on the model or the design. The top model had a feed rate of 25 four-foot lamps per minute and can contain about 800-1000 lamps per drum, while the lowest model can crush only a tube per minute and can hold about 60 four-foot lamps per container (Davis, 2001). Examples of commercial lamp crushing units are shown in Figure 2.3.

The larger scale fluorescent lamp crushing unit is a big crushing machine which has a high operating capacity and uses advanced technologies to control air emission. The feed rates of these units are between 3,000-4,000 tubes per hour (Davis, 2001). These units can not only crush the lamps, but sort the crushed material into glass, metal endcaps and phosphor powder also. In addition, some models have a retort system to recover mercury contained in the phosphor powder (Battye, 1994).
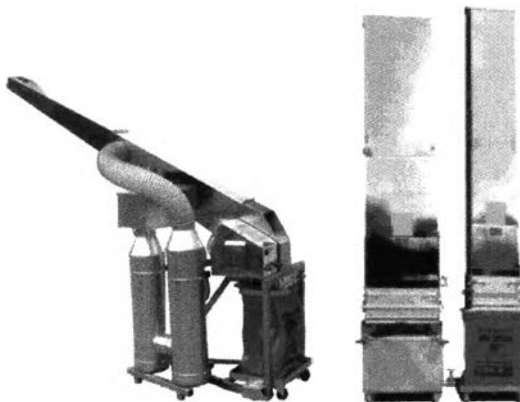
a) LC-55FDA-E and RULC-55DA-E lamp disposer, Dextrite, Inc.

Source: http://www.dextrite.com/Lamp_Disposers.htm

b) Bulb Eater Model 55-VRS, Air Cycle corporation

Source: http://www.dextrite.com/Lamp_Disposers.htm

c) Electric and Manual lamp crushers, Balcan Engineering

Source: www.balcan.co.uk/lamp/recycling.php

Figure 2.3 Commercial lamp crushing units: a) LC-55FDA-E and RULC-55DA-E lamp disposer, b) Bulb Eater Model 55-VRS, c) Electric and Manual lamp crushers.