UNIVERSITY OF NAIROBI

DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

FEB 540: DESIGN PROJECT

DESIGN OF A LAMP CRUSHER DEVICE FOR SAFE AND EFFICIENT CAPTURE OF MERCURY VAPOUR FROM FLUORESCENT LAMPS

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(April 2013)

A report submitted in partial fulfillment of a Bachelor of Science degree in Environmental and Biosystems Engineering in the University of Nairobi

DECLARATION

I hereby declare that this design project is my original work and has not been submitted for a degree award or its equivalent in any other university.

Signature……………………………………… Date……………………………………………….

Yvonne G. Mwangi

This design project has been submitted for examination with my approval as a University Supervisor.

Signature……………………………………… Date……………………………………………….

Dr. Muthumbi Waweru

DEDICATION

I dedicate this project to all my younger cousins, nieces and nephews. You can do anything you set your mind to. The sky is the limit.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor, Dr. Muthumbi Waweru, who has seen me through this project. I would also like to recognize Mr. Januarius Agullo for his contribution in the preparation of the project. I also appreciate all the lecturers of the Department of Environmental & Biosystems Engineering, beginning with the able chairman, Eng. Dr. Ayub Gitau for their teaching and mentorship throughout these five years.

I am grateful to my fellow students for their advice and friendship, to my parents, for being my steadfast encouragers, as well as my financial support, and to God, the Almighty, through whose strength I can do all things.

ABSTRACT

As the world grapples with the issue of global warming, there has been a shift away from energy-wasting incandescent bulbs to fluorescent lamps, which are more than four times more energy efficient and last up to 10 times longer. However, mercury is an essential ingredient in fluorescents and presents a problem when it comes to their disposal or recycling. Mercury in bulbs is mainly of elemental form, and 17-40% of it exists as a gas. This project was primarily concerned with capturing this toxic vapour, to prevent its escape into the atmosphere, and its eventual deposition in lakes and rivers. This was to be done by first crushing the bulbs to release the mercury vapour, and then directing the mercury laden air into a filter made of activated carbon, onto which the molecules of mercury would adsorb. A lamp crusher machine was designed for this purpose consisting of four main components: the carbon filter, the vacuum pump, the storage structure and the crushing unit. The machine, while designed to serve an environmental purpose, was also specifically designed to help address the problem faced by the Anti-Counterfeit Agency, which was storing three full shipping containers of fake fluorescents that it lacked the means of disposing of in an environmentally safe and legally sanctioned way.

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1 Introduction

1.1 Background

Mercury (chemical symbol: Hg, atomic number 80) is a poisonous metal found in fluorescent lamps, of which there are two types: tube lights and Compact Fluorescent Lamps (CFLs). When electricity is passed through mercury vapour in a phosphor tube, it produces short-wave ultraviolet light which then causes the phosphor to fluoresce, making visible light, unlike in incandescent bulbs where electric current runs through a wire filament and heats the filament until it starts to glow. Fluorescents tend to be about four times as energy-efficient as incandescent bulbs because they require less energy to provide lighting. They are also more cost-effective because they can last up to 10 times longer.

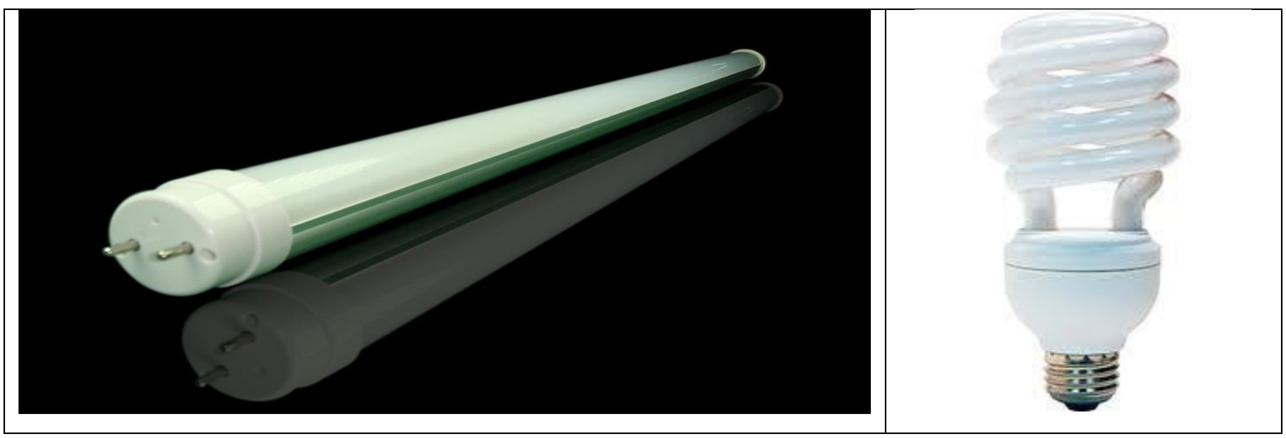


Figure 1: Fluorescent bulbs: Tube light (left) and Compact Fluorescent Lamp (CFL)

It is due to these advantages that the use of fluorescent bulbs is becoming more widespread as people try to cut down on energy costs. In 2009, a global initiative to accelerate the uptake of low energy light bulbs and efficient lighting systems was launched by the Global Environment Facility (GEF) and the United Nations Environment Programme (UNEP). Known as the “en.lighten initiative”, it is aimed at reducing the bills of electricity consumers in developing economies while delivering cuts in emissions of greenhouse gases (UNEP, 2009).

However, the presence of mercury in these lights renders them extremely dangerous when burst or broken. The elemental mercury contained in the bulbs quickly evaporates, particularly in warm or poorly-ventilated indoor spaces, jeopardizing the ambient air quality. (EPA) According to the United States Environmental Protection Agency (EPA), air borne mercury is highly toxic when inhaled, manifesting through tremors, headaches, insomnia, emotional changes and even at higher exposures, kidney failure and death. At the same time, mercury raises a problem in terms of lamp disposal. The consequence of carelessly discarding CFLs is the introduction of mercury into the soil and contamination of groundwater systems. When mercury enters bodies of water, biological processes transform it to methyl mercury, a highly toxic form. This leads to a phenomenon called bioaccumulation, as each organism higher up the food chain ingests an increasing concentration of mercury. Exposures to very small amounts of these compounds can result in devastating neurological damage and death. For foetuses, infants and children, it impairs neurological development and impacts cognitive thinking ability, memory, attention, language, fine motor skills, and visual spatial skills.

Each fluorescent bulb contains trace amounts of this substance, approximately 8-50 mg, but considering the potential number of these bulbs being used and discarded every day, it is clear that there is a need to develop a system or equipment for treatment of this waste for the environmental health of the country. This technology, while not yet being applied in Kenya, is being used in countries such as the United States of America. It works by separating the mercury vapour from the crushed glass of the bulb by creating a vacuum to suction the vapour out and trapping it in a filter, such as activated carbon (Davis, 2006). The filter is removable and can be replaced when full. The recovered mercury can therefore be utilized in industries that require it such as dentistry.

1.2 Problem Statement

Fluorescent bulbs are energy-efficient alternatives to the long-used incandescent bulbs. However, the mercury they contain renders the spent bulbs hazardous waste. Due to its volatility, mercury is emitted into the atmosphere and subsequently deposited in the soil and water bodies. Technology is therefore necessary which can safely capture the mercury and allow for the safe recycling or disposal of the glass component. Fluorescent lamp crushers are devices that allow size reduction for improved storage and transportation of used bulbs, as well as separation of mercury from the other components of the lights in order to ease disposal.

1.2.1 Problem Analysis

Globally, there has been a move towards increased use of fluorescents as a replacement for traditional tungsten-filament lights. This makes sense: Some 25% of the energy consumed by CFLs is converted to visible light, as compared to only 5% for an incandescent lamp. This means that up to 95% of the energy emitted by incandescent lamps is heat, and their efficiency is inherently low. Comparing the two types of lighting, incandescent bulbs last around 1,000 hours, which is significantly shorter than energy saving lamps, with life spans of 6,000 to 12,000 hours.

Use of fluorescent lamps promotes efficient energy use which is a stated goal of Vision 2030 (Vision 2030, p8). While exact numbers on the uptake of CFL are hard to come by in Kenya, it is a fair assumption that in urban areas at least, penetration rates are already relatively high. However, this development has not been accompanied by a proper waste recovery programme. There are no regulations in place specifically regarding the disposal of these bulbs. The national environmental body NEMA only states that hazardous waste, into which category spent fluorescents fall, must first undergo treatment to make it innocuous after which it can be safely disposed of.

The lack of proper regulation means that mercury may still be finding its way into the soil and into water systems, posing a potential health threat to both animals and human beings. One fluorescent tube contains enough mercury to pollute 30,000 litres of water beyond safe drinking level (source: Mercury Recycling plc). Fluorescent and other mercury-containing bulbs often break when thrown into a dustbin, or when they end up in a landfill or incinerator, releasing mercury vapour that can cause immediate problems like shortness of breath, chest pain, nausea, vomiting, and vision problems. Once in the atmosphere, elemental mercury can float for over a year while oxidized mercury compounds could drift several days before precipitating to the earth: soil or water(Jinjing, 2004). With no way to properly dispose of these lamps, an alternative is to stack and store spent bulbs in boxes, occupying storage space that might be otherwise utilized.

Although lighting manufacturers have greatly reduced the amount of mercury used in lighting over the past 20 years, they are not yet able to completely eliminate the need for mercury. According to National Electrical Manufacturers Association, (NEMA US) surveys, mercury use has been reduced dramatically over the last 7 years. Since 1990, NEMA US has conducted a number of surveys, which indicate the total amount of mercury contained in all lamps in the U.S. declined to 17 tons in 1994, 13 tons in 1999, 9 tons in 2001 and 7 tons in 2003—nearly a 90% reduction from previous years. Lamp types with high mercury content are, however, still reported to be on the market, and may be sold in large quantities as they are generally cheaper than low-mercury lamps. All this means that there is need for a way to capture mercury from the lights. The use of lamp crushing to reduce spent fluorescent tube lights helps to free up storage space, and more importantly, reduce the amount of mercury entering the environment from bulb disposal. This mercury can then be recycled separately from the other components of the bulbs, e.g. glass, metal and phosphor.

The table below shows that incinerating fluorescent bulbs carries the highest environment risk, whereas breaking of the bulbs inside the controlled conditions of a recycling chamber and recovering the mercury is the safest way of disposing of these bulbs. At the *point of release*, mercury concentrations are highest and the conditions for capture most favorable. (Manchester, 2004)

Table 1: Independent Impacts of lamp age at failure, Handling Conditions and Ultimate fate of Fluorescent Lamps on their Overall Mercury Impacts.

Lamp Age at Failure	Handling Conditions	Ultimate Fate	Environmental Impact
Accidentally broken when new (*no power plant emissions prevented, nearly all bulb mercury released*)	Broken indoors (*maximum health risk*)	Incinerator (*some mercury released to air*)	Highest
Fails before design life	Broken in open, leaky dumpster (*high risk of air and water pollution*)	Unlined landfill (*potential for air and water pollution*)	Moderately High
Achieves design life	Broken in transport or on landfill surface (some pollution likely)	Lined, monitored landfill	Moderate
Exceeds design life	Broken after burial in lined landfill (*most mercury contained*)	Hazardous waste landfill	Moderately Low
Greatly exceeds design life (*maximum power plant emissions prevented, most bulb mercury bound to glass or metal*)	Broken inside recycling chamber (*nearly all mercury recovered*)	Recycling facility (*nearly all mercury recovered*)	Lowest

Source: Ecos Consulting

1.3 Objectives

1.3.1 Overall Objective

The objective of this project was to design a lamp crushing device for the safe capture of mercury from fluorescent bulbs

1.3.2 Specific Objectives

- Establish the quantity of fluorescent lamps being held currently by the Anti-Counterfeit Agency
- Assess current disposal methods of these bulbs
- Identify the pertinent physical parameters which the design of the crusher will be based on.
- Design of the lamp crusher using the parameters identified

1.4 Statement of Scope

Although the topic of mercury recycling is wide and virtually inexhaustible, this particular project was limited to design of a lamp crusher for primary treatment of spent fluorescent bulbs, that is, capture of mercury vapour by means of a crusher. These light bulbs are crushed as the first step in recovery of mercury, or disposal of the bulbs in a landfill or incinerator. This document does not address the retorting of mercury-containing material for the recovery and recycling of elemental mercury, or the disposal of mercury-containing wastes, resulting from crushing operations.

1.5 Site Analysis

The Anti-Counterfeit Agency is a state corporation currently within the Ministry of Industrialization that was established under the Anti-Counterfeit Act of 2008 with the principal aim of prohibiting trade in counterfeit goods. The Agency came into operation in June 2010 with the mandates to enlighten and inform the public on matters relating to counterfeiting, combat counterfeiting, trade and other dealings in counterfeit goods, devise and promote training programs to combat counterfeiting and co-ordinate with national, regional or international organizations involved in combating counterfeiting.

In keeping with its mandate, the Agency has been able to intercept five containers of counterfeit fluorescent lamps imported into the country from China. The cargo comprised mainly fake Philips fluorescents of various sizes. Each container weighed between 35 and 40 tonnes and had an estimated value of KSh 10 million. However, as a result of a court order, two of the seized containers were returned to their owners. The other three are currently being stored in warehouses at the Agency’s expense. Two are in Kiang’ombe, Nairobi, and the remaining container is being stored in Mombasa.

The Agency must continue to store the lamps at a rate of KSh 422,400 annually per container because the National Environmental Management Agency (NEMA) regulates the disposal of the bulbs and has yet to license any facility in Kenya to treat and/or dispose of mercury-containing lamps.

2 Literature Review

Mercury is volatile. It vapourises at room temperature and increasingly rapidly as temperature increases. The vapour is an invisible, odourless and tasteless toxic gas. Its difficulty to perceive with our senses makes it more dangerous, as one may not even realize he is being exposed to it. Mercury is emitted into the atmosphere from both anthropogenic and natural sources, and because of its high volatility, subsequently enters oceans, lakes, and rivers directly from the atmosphere or from deposits in surrounding basins even when no specific source of mercury exists. (Fitzgerald et al, 1998)

Because of this, mercury-containing devices are classified as hazardous waste in many countries. Here in Kenya, according to the NEMA-authored Waste Management Regulations, 2006, Schedule IV, "wastes containing 0.1% or more by weight of…mercury" qualify as hazardous and must be treated before disposal. Traditional methods of disposal such as landfilling and incineration fail to take into account the volatility of mercury, resulting in its escape into the atmosphere and its subsequent deposition in water bodies.

It is for this reason that lamp recycling is the most environmentally sound and preferred disposal method for spent fluorescent lamps. Fluorescent lamp recycling refers to the reclamation of the materials of a spent fluorescent lamp. The process prevents the release of mercury into the environment by recovering it before the lamps are discarded**.** Although the amount of mercury in a single fluorescent lamp is small, (see Table 2) collectively, large numbers of fluorescent lamps contribute to the amount of mercury that is released into the environment. In the United States, about 620 million fluorescent lamps are discarded annually (National Electrical Manufacturers Association [NEMA US], 2000); proper recycling of a lamp prevents emission of mercury into the environment, and is required by most US states for commercial facilities. Landfill space is at a premium throughout the world and so the less waste that gets landfilled, the better.

Table 2: Mercury use in lamps sold by NEMA companies in 2004 (IMERC Fact Sheet, 2008)

Lamp Type	Amount of mercury per lamp (mg)	Per cent of lamps with specified mercury amount
Fluorescent tube	0 – 5 > 5 – 10 > 10 – 50 > 50 – 100	12 48.5 27 12.5
CFL	0 – 5 > 5 – 10 >10 – 50	66 30 4
High Pressure Sodium	>10 – 50	97

Figure 2: Improper discarding of fluorescent lamps

The biggest motivation for lamp recycling is that it prevents a significant amount of mercury from entering the environment. The Scientific Committee on Health and Environmental Risks of the European Union wanted to assess the effect of separate collection (and removal of mercury i.e. recycling) on the total Hg release into the environment. Assuming that each CFL contained 4.5 mg and that 20% were recycled, and using 2007 sales data, this resulted in a mercury emission in the environment of 1592 kg annually in the EU-27 area. However, increasing the recycling efficiency to 100% would have the effect of 71% less Hg being released. (SCHER, 2010)

Table 3: Effect of different recycling efficiency on the total environmental release of Hg. (SCHER, 2010)

Recycling efficiency (%)	Hg content of CFL (mg)	Hg release in environment (kg/y)
20	4.5	1592
50	4.5	1027
100	4.5	462

Virtually all components that make up fluorescent lights, including metal end caps, glass tubing, and phosphor powder, can be separated and recycled: The recycled glass tubing can be remanufactured into other glass products e.g. glass wool insulation; brass and aluminium in end caps is often sold as scrap metal; the internal phosphor coating can be reprocessed for use in paint pigments and as a bulking agent for fertiliser and the mercury contained in the lamp can be reclaimed and used in new lamps and other mercury-containing devices as well as a dental amalgam. The actual scrap value of the materials salvaged from a discarded lamp is insufficient to offset the cost of recycling which forces recyclers to charge fees for their services.

Many developed nations have recycling programs. Responsibility for recycling may fall on the municipal or state authorities, lamp producers, distributors or consumers. Common lamp recycling programs in the United States and in other countries include:

- Consumer mail-back programs, such as manufacturer and lamp recycler-sponsored recycling kits;
- Retail-sponsored collection programs at hardware and other stores, wholesale facilities, and other commercial locations;
- Utility-sponsored collection programs at a variety of locations;
- Publically-sponsored collection programs, such as household hazardous waste (HHW) collection facilities, municipal collection sites, and curbside recycling services; and

- Extended producer responsibility programs, such as the Waste Electrical and Electronic Equipment (WEEE) initiative in Europe, and similar programs in Asia. The WEEE directive requires producer responsibility for end-of-life management of certain products that contain mercury, lead, cadmium, chromium, and flame retardants like polybrominated biphenyls (PBB).

A mandatory lamp recycling program was instituted in Taiwan in 2002 by the Taiwan Environmental Protection Administration. Under the program, consumers can recycle lamps in any shop that sells them, and the collected lamps are sent to one of four mercury reclamation facilities. In 2003, about 87% of lamps were recycled in Taiwan **(**Hilken, C & Friesen, K, 2005). If each of those 78 million lamps had 5mg of mercury, this means that approximately 860 pounds of mercury was recovered.

Once at the recycling centres, the lamps undergo the following process:

1. *Material feeding* - certified waste fluorescent light tube are placed on a roller conveyer for further handling.
2. *End cutting* - The two ends of fluorescent light tubes are cut by flame or knives to separate fluorescent light tube and light cap. Since light tubes are damaged and mercury vapor is dispersed, machinery must be equipped with an exhaust system to pump mercury vapor to activated carbon absorption equipment. The separated cap is classified into three types of magnetic metal, non-magnetic mental, and lead (tube end) glass.
3. *Air jet cleaning* - High-pressure air is used to clean mercury from fluorescent powder and pump fluorescent powder to collection equipment for storage and then to mercury distillation equipment.
4. *Grinding and Screening* -This process includes tube end grinding and tube grinding. Tube end grinding uses a large machine to cut the end of the lighting product for the convenience of packaging and transportation operations afterwards. Magnetic and vibrating screening is done to sort copper, aluminum, and iron material out.
5. *Follow-up Treatment* - After handling, waste fluorescent light tubes generate six types of materials, tube (sodium) glass, tube end (lead) glass, fluorescent powder, mercury, iron, copper and aluminum. Fluorescent powder and end glass are sent to landfills; some tube

glass is landfilled, but the majority is recycled for re-utilization. Magnetic metal is also handled for reuse.

The Japan Fluorescent Lamp Recycling Company Ltd. uses “March 21” fluorescent lamp recycling equipment in its facilities. “March 21” is a recycling system that turns mercury into steam at a low temperature and recovering it. The boiling point of mercury is approximately 356.58℃, and high-temperature equipment of over 700℃ is normally required to convert mercury into steam and recover it. However, this technology can turn mercury into steam at lower temperatures between 250℃ and 300℃. Additionally, indirectly applying heated air to the rotary kiln can keep glass, aluminum and plastic substances from melting and sticking together, which can prevent the process from generating dioxin. (See Appendix 3 for process flowchart)

On a slightly smaller scale, one can employ crushing. The crushing of fluorescent lamps to separate the glass from the phosphor powder in the lamp is commonly the first step in recycling of mercury; although some companies use other methods, such as removal of the phosphor powder by air vortex or by flushing with hydrochloric acid. (Truesdale et al, 1993)

Drum-top crushing (DTC) is usually employed at the point where lamps are removed from service. DTC devices are designed to fit on the top of a drum (hence the name) in order to prevent the release of mercury vapours while crushing the fluorescent lamps into the drum below. These devices are used to reduce the volume of waste lamps so as to improve storage and handling and reduce shipping costs associated with fluorescent lamp recycling.

Lamp crushing is considered waste treatment because it changes the physical form of the waste and reduces volume to make storage and transport safer and easier. The most common type of crusher is the drum-top crusher (DTC). It consists of a vacuum-sealed container – a 55-gallon (210 litre) steel drum – in which glass fragments collect after passing through an entry tube and crushing mechanism. The mercury content of the lamp is contained by the vacuum and trapped in a filter arrangement, which must be replaced periodically. Spent fluorescent lamps are typically hand-fed into the entry tube, rapidly drawn into the drum by the vacuum seal and crushed in the motorized crushing assembly. Once the storage container is full, it is replaced and shipped to a recycling facility for processing. Mercury released as a vapour is collected in a distillation unit for sale or reuse. Secondary treatment might then include lamp retort (heating) to recover any mercury trapped in the crushed glass. Several companies manufacture fluorescent lamp crushers, including Dextrite, Air Cycle Corporation, and Resource Technologies. Drum-top lamp crushers are designed for use primarily in commercial and institutional facility management contexts.

Figure 3: Different types of drum-top crushers

The American Environmental Protection Agency (EPA) recently completed a drum-top crusher (DTC) study (EPA, 2006). The study was performed at three large-scale lamp-recycling facilities and evaluated the performance of three DTC devices. It showed that the performances of the devices diminished over their lifetimes and under varying environmental conditions. Minor mistakes in assembly of the devices could result in leaks. The effectiveness of the three devices in capturing and retaining mercury was evaluated using a mass balance. This was expressed as a percent of the total mass of mercury fed into the DTC device. For each device, the total mercury contained in enough lamps to fill one drum was estimated, and this quantity was then compared with the total mercury detected in samples collected during testing including: crushed lamps from the drum, DTC pollution control media (particulate, HEPA, and carbon filters), and analytical air samples. From the results, it appeared the efficiency of the lamp crushers was directly proportional to the mass of carbon used in the filter.

One major disadvantage was that the drums could only accommodate a certain number of lamps before they needed to be changed. When the drum beneath a DTC device was filled with crushed lamps, the DTC device had to be secured to a new drum. This operation involved unsealing the DTC device from the drum, lifting it off the drum, and placing it on a new, empty drum. During this operation, the full drum of crushed lamps would be open to the air for some period of time (approximately two to 10 minutes) during which mercury vapor is released uncontrolled to the air. During the process of changing from a full drum to an empty one, there existed opportunities for additional exposure of the operator to mercury vapour. Thus, by reducing the frequency of changes and/or minimizing the time during which the full drum is open to the air, one would be able to limit mercury exposure. Nevertheless, throughout the study, all three devices maintained mercury levels below Occupational Safety and Health Administration (OSHA) time-weighted average requirements within the containment structure and in the operator breathing zone.

There are companies that specialize in lamp recycling such as the UK-based, Balcan Engineering. The Balcan recycling plant in Lincolnshire can process approximately 750 tonnes of waste lamps per annum. It has products varying from devices for specific types of bulb recycling to fully-fledged recycling plants. The recycling plant essentially utilizes the lamp crusher method, but on a much larger scale. It works like this: Whole and pre-crushed fluorescent tubes are input into a hopper. From there, they move to an agitator where they are reduced in size and from which glass and aluminum are separated. The agitation of pieces knocking and rubbing against each other removes much of the adhering powder from the surface of the glass. The remaining debris is passed through the Dust Removal Filter which draws off the dusty air (comprising of phosphor powder and fine glass particles) down to 5-micron size. This also ensures that the whole plant operates under negative pressure so dust and vapour does not escape into the workplace. Finally, the Activated Carbon Stack which is used to remove exceptionally fine dust below 5-microns and mercury bearing vapour (that cannot be removed from the air in any other way) before release to the outside atmosphere.

Figure 4: Tubes ready for processing at the Balcan plant

In addition, Balcan operates a fleet of vans, each fitted with an electrically operated crusher. The mobile crushers use a fan-assisted filtration unit to draw off the dust during crushing. In this way the machine also operates at negative pressure. The extractor is positioned in the chute because fluorescent tubes can inadvertently burst anywhere along their length so it is essential to capture the resultant dust as it is generated. Balcan has added a spring-loaded sealing plate to their mobile crushing equipment which is designed to prevent escape of mercury vapour during the crushing process. Debris from the crushers discharges directly into strong plastic sacks holding an average of 25-27 kg of debris. And the recycling operation as described previously begins when the debris sacks are emptied into a hopper at the plant.

Another method of treating lamps is to combine the mercury with sulphur to form mercury sulphide, which is insoluble in water (Gorin et al., 1994). One advantage of sulphur is its low cost. The reaction is shown with the equation:

$$Hg + S \rightarrow HgS$$

The easiest way to combine sulphur and mercury is to cover a group of fluorescent tubes with sulphur dust and break them; when the glass is put into a bag to continue with the reaction, the mercury will combine with sulphur without any other action. The glass can be recycled where an appropriate facility exists. A quantity of 25 kg of dust sulphur is enough for 1000 tubes.

Research on the subject of lamp recycling is still on-going. Engineers from Brown University tested 28 different chemicals to collect spilled mercury from CFL breaks. The best performer was amorphous nanoselenium particles no more than 60 billionths of a meter in diameter. In lab tests, the orange nanoparticles trapped and neutralized 99.9 per cent of the mercury vapor they encountered (Hurt, 2009). They proved so potent that just a few milligrams rendered inert a milligram of mercury — an amount comparable to what a broken CFL would release. In comparison, quantities in excess of 10 kilograms of powdered sulfur or zinc would be needed to neutralize a milligram of mercury.

Lamp recycling is a wide field with many players and nearly as many available methods. Each method of recycling has potential benefits and draw-backs. This project, however, will focus on the design of a lamp crusher for capture of mercury from fluorescent bulbs.

3 Theoretical Framework

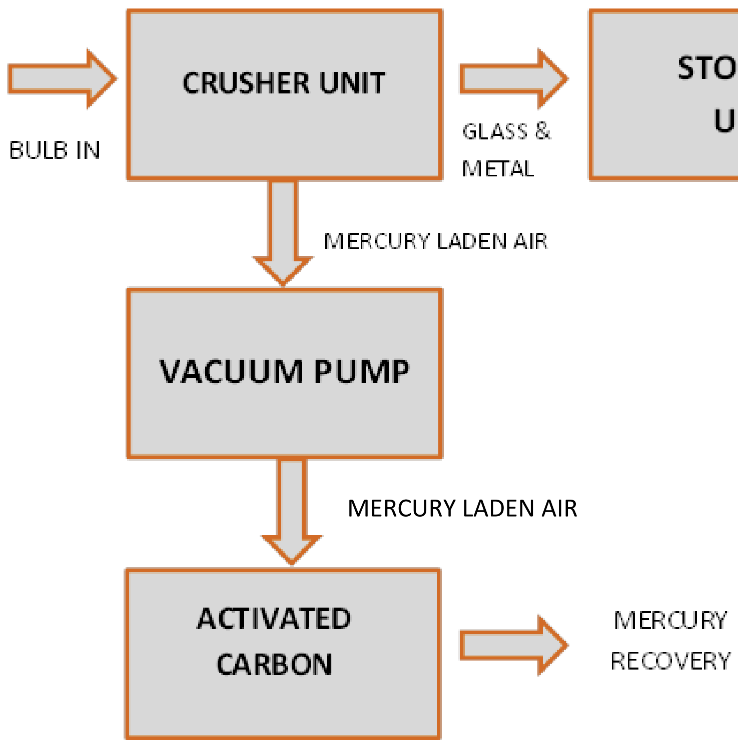


Figure 5: The lamp crushing process

The major components of the device are:

1) Activated carbon filter –adsorbs mercury from air within crusher

2) The storage unit – into which the glass and metal parts fall

3) The vacuum pump – lowers the pressure inside the device and directs air containing mercury vapour into filter

4) The crusher unit – motor, rotor and chains to break the lamps

3.1 Adsorption by Activated Carbon

During the process of adsorption, the gas stream passes through a bed or layer of highly porous material called the adsorbent. The compound or compounds to be removed, termed the adsorbate(s), diffuse to the surface of the adsorbent and are retained because of weak attractive forces, while the carrier gas passes through the bed without being adsorbed.

The adsorption process is classified as either physical or chemical. In physical adsorption, the molecules are retained at the surface in the liquid state because of intermolecular or Van der Waals forces. The chemical nature of the adsorbed gas remains unchanged; therefore, physical adsorption is a readily reversible process. In chemical adsorption a strong chemical bond is formed between the gas molecule and adsorbent. Chemical adsorption, or chemisorptions, is not easily reversed.

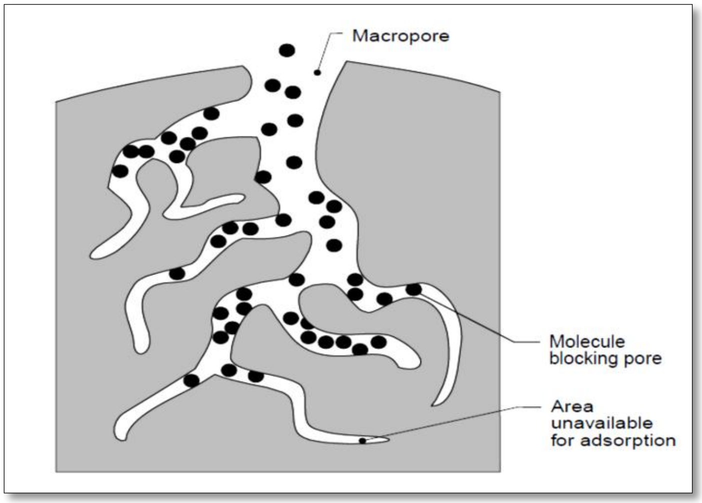


Figure 6: Vapour adsorbed into pores of adsorbent

Carbon is a commonly used adsorbent due to its very large surface area (500 to 1,600 m^2/g). It can be made from a variety of base materials including coal, wood and coconut shells and petroleum-based products, and is manufactured in two steps: First, the raw material is pyrolized i.e. it is heated to about 5900C in the absence of oxygen to drive off all volatile material. Next, it is activated using steam, oxygen or carbon dioxide at high temperatures to attack the carbon and increase the pore structure.

Activated carbons used in the air pollution control field are normally supplied in a granular form with a particle size ranging from 1 to 5 millimeters. In the granular form activated carbon can easily be packed into a containment device through which a contaminated gas stream can be processed for purification. Most adsorption systems consist of one or more vessels connected in series or in parallel. These vessels can be cartridges, canisters, drums, tanks, or bins.

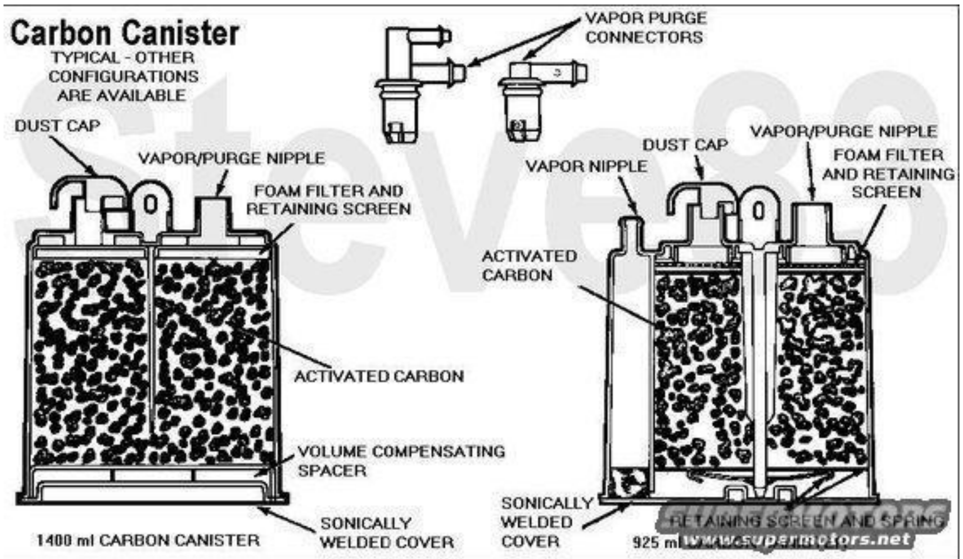


Figure 7: Carbon canister

There are three things that are necessary for adsorption of mercury using activated carbon:

1. Containment device – a drum or vessel
2. Distribution and collection devices – for proper circulation of gas stream through filter bed
3. Means of moving the gas through the means for moving the gas stream through the bed (such as a fan, a blower, or pressurized gas displacement

Each adsorbing material has a different adsorption capacity referred to as the "adsorption isotherm." The adsorption capacity for a particular contaminant represents the amount of the contaminant that can be adsorbed on a unit weight of activated carbon consumed at the conditions present in the application until breakthrough occurs. This isotherm is a function of the contaminant concentration (or partial pressure) in the vapor, the temperature, the total ambient pressure, and the surface area of the carbon.

$$Adsorptive\ capacity = \frac{mass\ of\ impurity\ adsorbed}{mass\ of\ carbon}$$

Adsorption also depends on the gas velocity – the lower the velocity, the longer the contact time through the adsorbent and the greater the probability of a contaminant molecule reaching an available site. Appropriate velocities run from 6-30m/min.

To determine velocity:

$$gas\ velocity\ (m/min) = \frac{gas\ volumetric\ flow\ rate\ \ (m3/\mathrm{min})}{cross - sectional\ area\ of\ bed\ (m2)}$$

Once the activated carbon has become spent it must be removed from service and replaced with fresh carbon in order to maintain the effectiveness of treatment. The spent carbon can be disposed of and replaced with virgin carbon, or the spent carbon can be returned to the supplier for reactivation and reuse. The process of removing the adsorbent is called regeneration of the adsorbate. It is done by either increasing the temperature or decreasing the pressure. It must be noted that, in practical applications, adsorbers use more carbon than is required at saturation to ensure that uncaptured vapors are not exhausted to the atmosphere.

There is no theoretical method that consistently and accurately predicts the performance of adsorption systems (Rafson 1998). Carbon adsorption is based on the principle of equilibrium partitioning from the vapor phase to the surface of the carbon. The carbon adsorption capacity is strongly influenced by the contaminant concentration in the process stream and the temperature at which the adsorption is taking place. In general, the higher the concentration of contaminant in the vapor stream, the higher the contaminant adsorption capacity of the carbon. Conversely, the higher the temperature, the lower the adsorption capacity. (Jinjing, 2004) Most carbon manufacturers have empirical adsorption isotherm data (adsorption capacity as a function of concentration at a constant temperature) used to predict when the adsorption capacity of a particular adsorbent will be reached for specific contaminants at varying influent concentrations.

3.2 Mercury vapour state

Mercury can exist in 3 states of matter: Liquid, Solid and Gas. It has freezing point of -38.9°C (234K) and a boiling point of 356.58°C (630K). Standard values are used for mercury molecular weight (200.6), density (13.5 g/cm3), and vapor pressure (0.0018 mm at 298°K).

It is the only metal that exists as a liquid at room temperature and pressure. In fluorescent bulbs, mercury is used to convert electrical energy to radiant energy in the ultraviolet range, which is then re-radiated in the visible spectrum by the "phosphor" compounds that coat the inside of the bulb.

Mercury exists in elemental form (Hg0) as a silver-colored liquid, or as mercury vapor in the atmosphere (Schroeder, 1982). Many forms of mercury, including elemental, are volatile enough so that a significant portion can exist in the gaseous state. Once a CFL has been broken, mercury vapor, liquid mercury (if present), and mercury adsorbed onto the phosphor powder will be released. It is unlikely that any spilled liquid mercury will be visible as the volume of mercury is small and any spilled mercury would form minute droplets on impact. The phosphor powder can separate from the glass when the lamp is broken. Although it is believed that most of the volatile mercury in the bulbs is elemental, other volatile mercury compounds and powders may be released.

The air reaching the activated carbon will be a mixture of a number of gases, including the gas of interest in this project: mercury vapour. To obtain the partial pressure of mercury vapour, we must consider Dalton's Law:

The pressure of a mixture of gases is equal to the sum of the partial pressure of the constituents.

The partial pressure of each constituent is that pressure which the gas would exert if it alone occupied that volume occupied by the mixture at the same temperature and pressure.

Therefore in a mixture of gases, pressure would be given by:

$$p = \sum p_i$$

Where pi is the partial pressure of each constituent gas.

Similarly, volume of a mixture of gases is:

$$V = \sum V_i$$

Partial pressure is also related to the number of moles of a substance as well as the volume by the following:

$$\frac{p_i}{p} = \frac{V_i}{V} = \frac{n_i}{n}$$

Where n is the number of moles of a substance.

The amount of mercury per volume of mercury saturated air depends on the temperature of the mercury saturated air. This relationship is described by the Ideal Gas Law. An ideal gas can be characterized by three state variables: absolute pressure (P), volume (V), and absolute temperature (T). In such a gas, all collisions between atoms or molecules are perfectly elastic and in which there are no intermolecular attractive forces. One can visualize it as a collection of perfectly hard spheres which collide but which otherwise do not interact with each other. All the internal energy is in the form of kinetic energy and any change in internal energy is accompanied by a change in temperature.

In short, an ideal or perfect gas is one that is subject to the Ideal Gas Law.

$$pv = RT$$

Where:

p= absolute pressure (bar)

R = specific gas constant (Nm/Kg K or kJ/Kg K)

T = temperature (0C)

v = specific volume (m3/kg)

For a mass, m, occupying a volume, V, the equation may be written as:

$$pV = mRT$$

In terms of the amount of substance (mole), the law becomes:

$$pV = n\widehat{m}RT$$

Where:

n = amount of substance (mol or kmol)

$\widehat{m} = \frac{m}{n}$ =molar mass (kg/kmol)

3.2.1 Storage Unit

This is where the lamp debris fall after crushing. Its volume will depend on the number of lamps to be crushed and will be calculated by:

$$V = L \times B \times W$$

3.2.2 Sizing the motor

3.2.2.1 Failure of Materials

The behavior of materials can be broadly classified into two categories; brittle and ductile. Steel and aluminum usually fall in the class of ductile materials. Glass and cast iron fall in the class of brittle materials. Every material will perform differently under the application of stress and strain and therefore each material's graph will be different. considerable amounts of information can be identified and collected from a Stress-Strain graph.

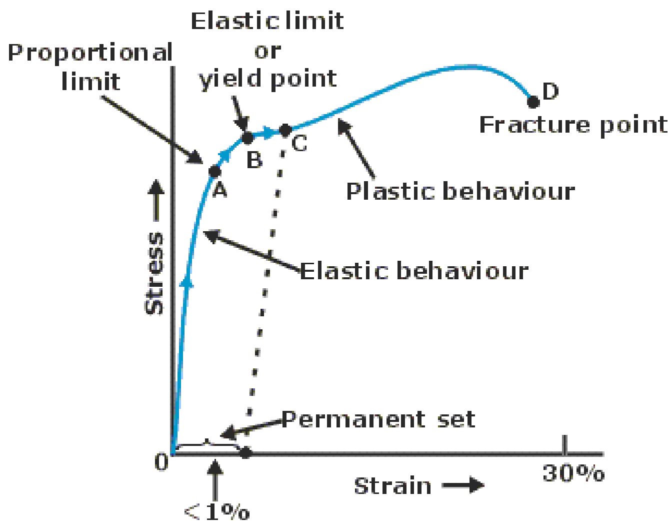


Figure 8: Stress-Strain Curve

Some of the graph's most important aspects are:

- ✓ The **elastic region** -For most materials the elastic region is illustrated by the initial straight line
- ✓ **Yield stress**
- ✓ **Plastic flow region**- The plastic flow region is illustrated by the curved line that ends at the "rupture stress" point.
- ✓ **Ultimate stress (UTS)** -The ultimate tensile stress is the maximum stress recorded throughout the continued stress application.
- ✓ The **rupture stress** is the maximum instantaneous stress at the breaking point of the material.

After the yield point, the curve will dip slightly then the stress will increase because of strain hardening. Finally, the graph will reach its ultimate tensile strength. Hence forth the material becomes unstable and fractures.

The material response for ductile and brittle materials is exhibited by both qualitative and quantitative differences in their respective stress-strain curves. Ductile materials will withstand large strains before the specimen ruptures; brittle materials fracture at much lower strains. The yielding region for ductile materials often takes up the majority of the stress-strain curve, whereas for brittle materials it is nearly nonexistent. Brittle materials often have relatively large Young's moduli and ultimate stresses in comparison to ductile materials. Their rupture and ultimate strength is the same, so the curve has only the straight elastic region then the rupture. These differences are a major consideration for design. Ductile materials exhibit large strains and yielding before they fail. On the contrary, brittle materials fail suddenly and without much warning.

Stress, is the force per unit area (N/m^2)

$$\sigma = \frac{F}{A}$$

Whereas strain is the relative change in shape or size of an object due to externally applied forces;

$$\varepsilon = \frac{change\ in\ length}{original\ length} = \frac{\Delta l}{l}$$

The two are related by Young’s modulus:

$$E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon}$$

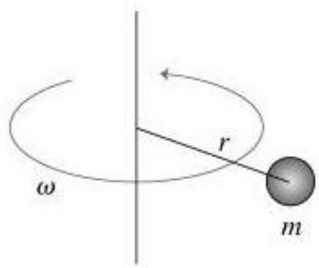
3.2.2.2 Newton’s Laws of Motion

Mechanics is governed by Newton’s Laws of Motion:

1. *Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it (Law of Inertia)*

2. *The change of momentum per second is proportional to the applied force and the momentum change takes place in the direction of the force. (*F = ma).
3. *For every action there is an equal and opposite reaction.*

The crusher unit is made up of the motor, which runs the rotor-and-chains that actually shatter the lamps. In order to design a system which can effectively crush the lamps, we must consider the torque and angular acceleration of the chains, and the moment of inertia.



The angular acceleration of an object spinning about its centre is given by:

$$\alpha = \frac{\omega - \omega 0}{t}$$

Where ω = final angular velocity; ω_0= initial velocity; t = time

To make the wheel spin faster, a torque, T is applied to the wheel. The turning effect or torque of a force, F applied tangentially to a wheel of radius, r spinning about its centre is given by $T = F \times r$ (Nm). According to Newton's second law, F=ma. In rotational motion, this can be analogized as:

$$T = I\alpha$$

Where I is the **moment of inertia**. The moment of inertia, *I* , of a rigid body gives a measure of the amount of resistance a body has to changing its state of rotational motion. Mathematically,

$$I = \sum m_i r_i^2 \text{ (kg m}^2\text{)}$$

i.e. the sum of all the products mr^2 for the masses m of the object and the square of their distances from the axis of rotation.

Once the torque, angular acceleration have been determined, a motor that provides the necessary operating speed and load torque can be obtained. An electric motor is a device that converts electrical energy into mechanical energy. Electric motors convert voltage into speed and current into torque:

Calculating torque

Torque (in Newton-metres) is given by:

$$T = K_t \emptyset I_a \quad \text{or} \quad \Gamma = K_t . I$$

Where:

- $Kt = \text{constant} = \frac{pZ}{\pi C}$
- Ia= armature current (Amperes)

Calculating speed

$$\omega = Kb * V$$

where V = supply voltage; Kb = constant

The product of the torque and the speed of the motor gives the power:

$$P = T\omega \text{ (Kw)}$$

3.2.3 Vacuum Pump Theory

While in operation, most lamp crusher systems are designed to provide a negative pressure in the collection container to prevent the release of mercury and dust into the ambient air. A **vacuum pump** is a device that achieves this by removing gas molecules from a sealed volume in order to leave behind a partial vacuum.

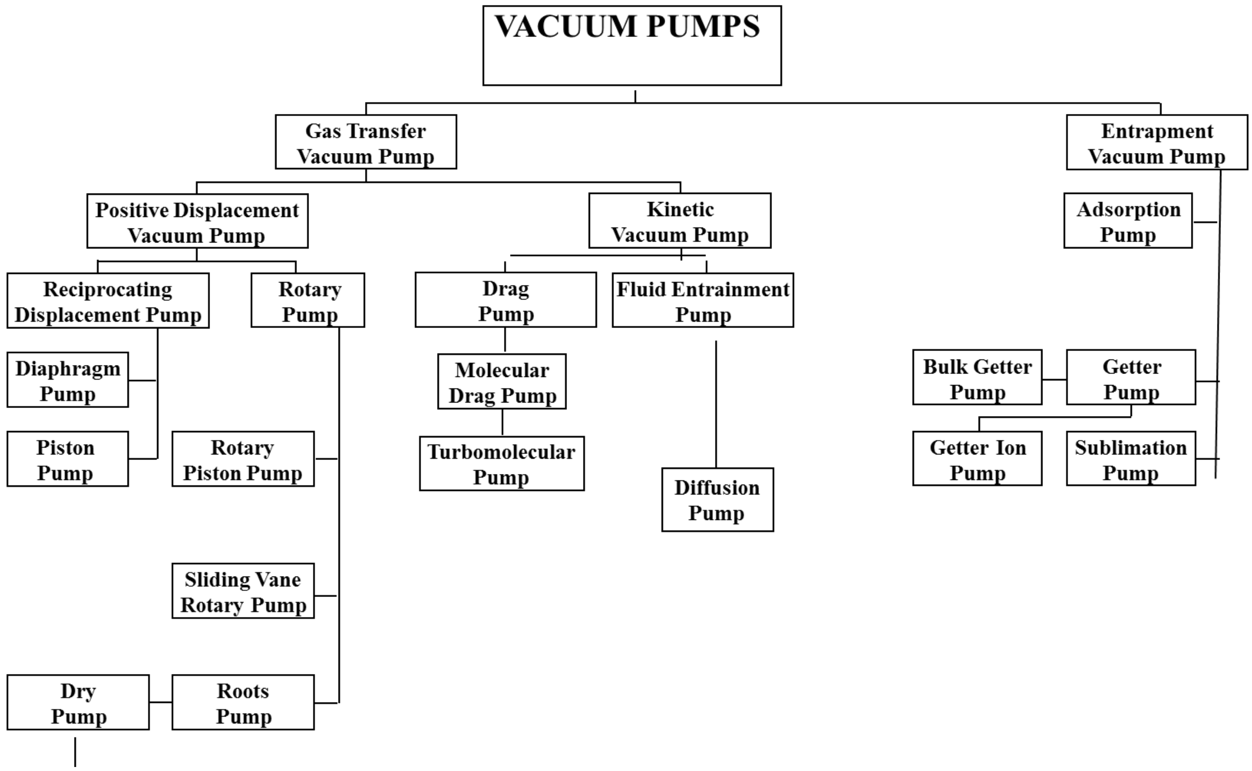


Figure 9: Types of vacuum pumps

3.2.3.1 Vacuum Pumps: Basic Operation

A vacuum pump converts the mechanical input energy of a rotating shaft into pneumatic energy by evacuating the air contained within a system. The internal pressure level thus becomes lower than that of the outside atmosphere. The amount of energy produced depends on the volume evacuated and the pressure difference produced.

Rotary positive displacement pumps are the most effective for low vacuums. Positive displacement refers to the fact that during operation the pump periodically creates increasing and decreasing volume to remove gases from the system and exhausts them into the atmosphere. The rotor is eccentrically mounted in the stator and carries two blades which sweep the space between the rotor and the stator. (Fig.9b) The gas being exhausted enters through the vacuum connection and is compressed before delivery through the discharge valve. The efficiency is impaired by the presence of condensible vapours. Condensible vapours can only be compressed to their saturated vapour pressure. Further compression will not increase the pressure of the gas.

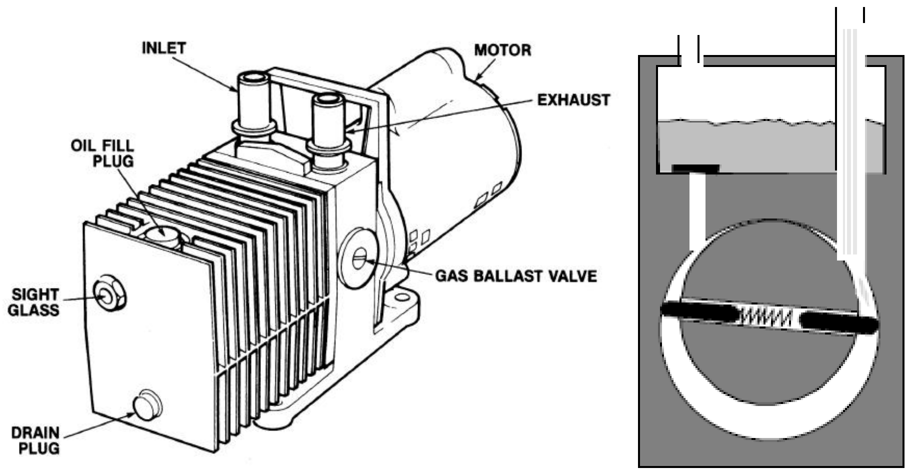


Figure 10: Outer view (left) and principle of operation of a vacuum pump

3.2.3.2 Positive Displacement Vacuum Pumps

Vacuum pumps are either positive displacement or nonpositive displacement machines. A positive displacement pump draws a relatively constant volume of air despite variations in the vacuum levels.

- **Reciprocating Piston Pumps** -The primary advantage of the piston design is that it can generate relatively high vacuums from 27 to 28.5 in. Hg (0.91-0.97 bar) -and do so continuously under all kinds of operating conditions. The major disadvantages are somewhat limited capacities and high noise levels, accompanied by vibrations that may be transmitted to the base structure. In general, the reciprocating piston design is best suited to pulling relatively small volumes of air through a high vacuum range.
- **Diaphragm Pumps** -The diaphragm unit creates vacuum by flexing of a diaphragm inside a closed chamber. Small diaphragm pumps are built in both one- and two-stage versions. The single stage design provides vacuums up to 24 in. Hg (0.81 bar), while the two stage unit is rated for 29 in. Hg (0.98 bar).
- **Rocking Piston Pumps** -This design combines the light weight and compact size of the diaphragm unit with the vacuum capabilities of reciprocating piston units. Vacuums to 27.5 in. Hg (0.93 bar) are available with a single stage; two-stage units can provide vacuums to 29 in. Hg (0.98 bar). Air flows, however, are limited, with the largest model available today (a twin cylinder model) offering only 2.7 cfm.

- **Rotary Vane Pumps** -Most rotary vane pumps have lower vacuum ratings than can be obtained with the piston design: only 20 to 28 in. Hg maximum (0.68–0.95 bar). But there are exceptions. Some two stage oil-lubricated designs have vacuum capabilities up to 29.5 in. Hg. The rotary vane design offers significant advantages: compactness; larger flow capacities for a given size; lower cost (about 50 percent less for a given displacement and vacuum level); lower starting and running torques; and quiet, smooth, vibration free, continuous air evacuation without a receiver tank.
- **Rotary Screw and Lobed Rotor Pumps** - Vacuum capabilities of rotary screw pumps are similar to those of piston pumps, but evacuation is nearly pulse-free. Lobed rotor vacuum pumps, like the corresponding compressors, bridge the gap between positive and nonpositive displacement units. Air flow is high but vacuum capabilities are limited to about 15 in. Hg (0.5 bar). Capabilities can be improved with staging.

3.2.3.3 Nonpositive Displacement Vacuum Pumps

Nonpositive displacement vacuum pumps which include centrifugal, axial-flow, and regenerative designs, use changes in kinetic energy to remove air from a system. The most significant advantage of this design is its ability to provide very-high-volume flow rates-much higher than possible with any of the positive displacement designs. But because of their inherent leakage, these machines are not practical for applications requiring higher vacuum levels and low flow rates.

For a rotary vane pump, the volumetric flow rate at which gas is swept around the pump is:

$$S = 2Vn$$

Where: V = volume of gas between the rotating blades or vanes
n= no. of rotations per unit time (rpm) (usually 350-700 r.p.m.).

The compression ratio is the ratio of the pressure of the exhaust gas (atmospheric pressure) to the pressure of the gas at the inlet (base pressure) i.e.

$$K = {}^{Pout}/_{P\ in}$$

Vacuum pumps have two operating characteristics: base pressure and pumping speed.

The speed listed on any given pump is usually the free air displacement at STP. As pressure decreases from atmospheric, there will be a reduction in the amount of gas pumped per unit time (mass flow rate). Pumping speed will decrease only slightly until a pressure of about 1 Torr is attained.

Speed can be measured at constant volume by the equation:

$$S = 2.3\left[\left({}^{V}/_{t2 - t1}\right)\log\left({}^{P1}/_{P2}\right)\right]$$

Where: V = volume of vessel (litres)
T1 = time at pressure P1(sec)
T2 = time taken to achieve pressure P2 from P1 (sec)

Constant pressure method:

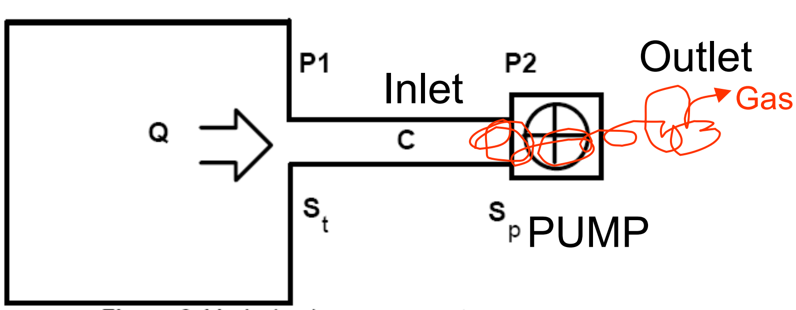
$S = Q/P$

Where:P = pressure (Torr); S = speed (litres/sec); Q = mass flow rate (Torr-litres/sec)

Quantity of gas removed by the pump at a steady state pressure, P, is the mass flow rate of the gas, or throughput.

Evacuation Time

The evacuation time of a pump is the time taken to evacuate the system from initial pressure to a final pressure.



It is given by the equation:

$$t = \frac{V}{S} \ln(\frac{P_0}{P_1})$$

Where: V = volume of vessel (m^3)
P0 = initial pressure (bar)
P2 = final pressure (bar)
S= actual suction capacity (m^3/min)

Conductance

Gases moving through conductance elements (pipes, tubes, vessels, and orifices) in a vacuum system encounter resistance to their motion. At higher pressures, this resistance is a function pressure difference and geometry of the conductance element.

$$C = {}^{Q}/_{P2 - P1}$$

P1, P2 are as shown in the figure above.

4 Methodology

4.1.1 Data collection

Data regarding the number and fate of fluorescent bulbs at the site were obtained by desk study and interview. Policy and legal data regarding the fate of fluorescent lamp waste was obtained from the National Environmental Management Authority (NEMA) again by desk study and interview with various officers.

4.1.2 Activated carbon adsorption analysis

The adsorptive capacity of the activated carbon was found and used to determine the number of lamps that could be crushed before the carbon would have to be replaced.

The number of bulbs required to saturate the activated carbon was given by:

$$\frac{Adsorptive\ capacity\ of\ Activated\ Carbon\ (g)}{mass\ of\ mercury\ vapour\ per\ bulb\ (g)}$$

To obtain the time before activated carbon reached saturation capacity, The amount of mercury entering the system every minute is was estimated by:

$$m = R \times M$$

Where m = mass of activated carbon entering the system per minute
R= rate of feeding bulbs
M= mass of Hg vapour per bulb

So to saturate the carbon at this mass flow rate would take time, t:

In hours:

$$t = \frac{saturation\ capacity\ of\ activated\ carbon\ (g)}{mass\ flow\ rate\ (\frac{g}{s})}$$

The rate at which the bulbs existing at the site would be processed through the crusher was then determined.

Number of lamps crushed per day:

$$= \frac{No. of\ lamps\ needed\ to\ saturate\ the\ carbon}{no. of\ days\ needed\ for\ carbon\ to\ get\ saturated}$$

Using the relative volumes therefore, the number of lamps per container was estimated as:

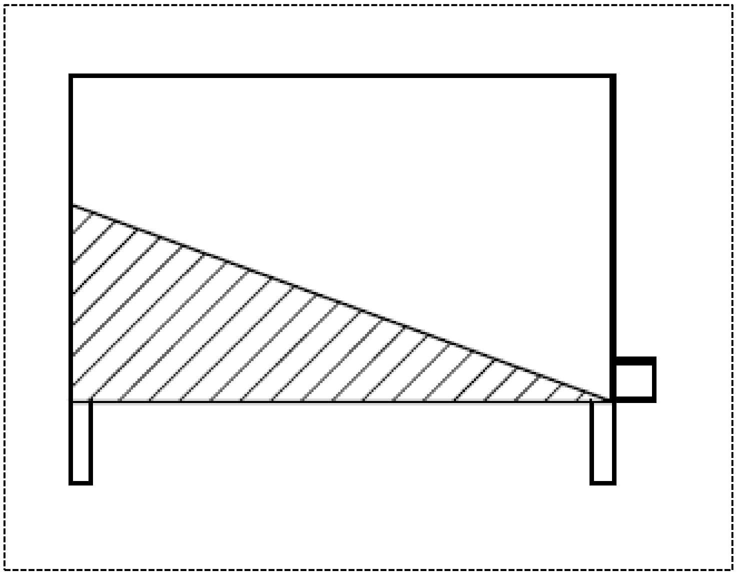
$$= \frac{volume\ of\ container}{volume\ of\ one\ lamp}$$

Time taken process all the lamps in one container:

$$= \frac{number\ of\ lamps\ per\ container}{number\ of\ lamps\ crushed\ per\ day}$$

4.1.3 Storage Unit sizing

The volume of the storage unit was then calculated, keeping in mind that the bulbs were to be crushed and stored in batches. The volume of one batch was used to size the unit.



The section was divided into two shapes whose volumes could be easily calculated.

So the volume of the rectangular section was:

$$V = L \times B \times W$$

And the volume of the triangular section was:

$$V = \frac{1}{2} bh.width$$

4.1.4 Motor sizing

The first step in this process was finding out how much force would be required to break the glass. Now glass is a brittle material, such that it yields very quickly under a load. Because the glass would break by shearing the shear strength was pertinent.

$$\sigma = \frac{F}{A}$$

This strength was used to find the force required to shatter the glass, which in turn was used to find the torque required by the motor.

$$T = F \times d$$

Using IEC standard motor curves, the torque was related to the synchronous speed.

The product of the torque and the speed of the motor gave the power:

$$P = T\omega \text{ (Kw)}$$

If power output is measured in Watt, efficiency can be expressed as:

$$\eta m = Pout / Pin \qquad (1)$$

Where η_m = motor efficiency
P_{out} = shaft power out (Watt, W)
P_{in} = electric power in to the motor (Watt, W)

The efficiency was also based on IEC standards. International Electrotechnical Commission (IEC), a global non-governmental organization that prepares and publishes international standards for electrical, electronic and related technologies. Several of its standards are highly relevant for motor manufacturing. IEC 60034 is referred to by regulators for the classification of electrical motor efficiency.

4.1.5 Vacuum pump sizing

The vacuum pump was sized for the required pressure using by rearranging the evacuation time equation

$$t = \frac{V}{S}\ln(\frac{P_0}{P_1})$$

such that S (Pump capacity) became the subject:

$$S = \frac{V}{t}\ln(\frac{P_0}{P_1})$$

This value of S, also known as the volumetric flow rate, was then used to calculate the mass flow rate of the fluid (air) using the equation:

$$Q = PS$$

Where Q represents the mass flow rate.

Finally, the power of the pump required was obtained from a commercial power-vacuum curve since it varies from manufacturer to manufacturers.

5 Results and Discussion

For the design calculations, please see Appendix 2

5.1.1 Data collection

The Anti-Counterfeit Agency is the authority in Kenya mandated with preventing the sale of counterfeit goods in the country. By means of desk study as well as interviews with a representative of the Agency, I was able to determine that since 2011, they had intercepted five Chinese-sourced shipping containers of fake fluorescent bulbs destined for sale on the Kenyan market. However, as at the time of the interview, two of the containers had been returned to their owner through court order. The rest are being warehoused in Mombasa and Nairobi. Below is a summary of the information contained and subsequently used in the analysis.

Table 4: Summary of collected data

Number of containers in Storage	3
Mass of each container	30-35 tonnes
Outside dimensions of each container	**Outside Length:** 12.2m / 40ft **Outside Height:** 2.6m / 8ft 6in **Outside Width:** 2.44m / 8ft
Inside dimensions	**Internal Length:** 12.04m / 39ft 6in **Internal Height:** 2.39m / 7ft 10in **Internal Width:** 2.35m / 7ft 8in
Cubic capacity:	67.6 cubic meters
Type of lamps in container	Philips fluorescents, assorted sizes
Annual cost of storage per container	KSh 422, 400

Note: All the calculations assumed that the sizes of lamps were all 4-foot lamps. This is because generally, the 4-foot lamp is the highest volume lamp sold, (Environment Canada,2001) accounting for approximately 75 percent of the market

A typical fluorescent bulb discarded today is likely to contain an average of approximately 20 mg mercury (Environment Canada, 2001) where the mercury in vapour form is between 17 and 40% (Aucott, 2004). This information was useful in determining the rate at which activated carbon would be used up. By calculation, this was found to be 26 days or once per every 250000 bulbs. It is important to note that this was for 10kg of activated carbon with an adsorbent capacity of 15%. The rate of replacement is primarily a function of the absorbency of the charcoal.

The rate of crushing the bulbs was over 9600 a day, meaning that the entire confiscated shipment could be destroyed in 36 days. Compare this with the fact that the oldest container had been stored since 2011, more than 700 days, and it is clear what the advantages of the lamp crusher are.

The next step taken was to work out the storage unit volume**.** The storage unit is where the debris from crushing falls whilst the mercury-laden air is drawn into the activated carbon filter. The crushed glass, phosphor and metal end caps are stored for a time before being collected for disposal or recycling. Typically, the crusher reduces the volume 6-8 times for whole lamps (MRT Technologies). A convenient value of 10000 lamps per batch was chosen to ease calculation. The volume of the whole lamps was found, then divided by a factor of 6 to represent the volume reduction. The final volume was 1.03m3 and the crusher was to have dimensions of 1.5×1m. The height varied due to the slope of the floor of the structure. These dimensions are reflected in Drawings in Appendix 1 in centimetres to the nearest whole number for ease of measurement. The storage unit would ideally be constructed of a hard material to resist wear by abrasion from glass shards – sheet metal such as mild steel.

Following this, the motor that would be able to perform the task of crushing the bulbs had to be chosen. The first step in this process was finding out how much force would be required to break the glass. Now glass is a brittle material, such that it yields very quickly under a load. Because the glass would break by shearing the shear strength was pertinent. This was obtained from a table of properties (Appendix 3) of silica glass, the type of glass used for such tube lights, as 70000N/m^2. This strength was used to find the force required to shatter the glass, which in turn was used to find the torque required by the motor. Using IEC standard motor curves, the torque was related to the synchronous speed. The synchronous speed of a motor is a function of the number of poles. Most commonly used motors nowadays are 2 and 4-pole motors, and so a 4-pole version was selected with a no-load speed of 1500 rpm. Having the torque and the speed then made it possible to calculate the power of the motor as 1.5443 kW. The IEC standards (IE-60034-30, 2008) (Appendix 3) were used to find efficiency of the motor in order to select the optimum motor for the job. The conclusion was that a 2.2kW (3hp) motor would be acceptable.

When it came to the vacuum pump, the most important factors were the actual suction capacity (m3/s or Litres/min), and the power (kW). The capacity, also known as the volumetric flow rate, was worked out for a vacuum of 100mbar at standard temperature of 250C. It worked out to 200 Litres/min. This flow rate also made it possible to work out the mass flow rate using the relation Q=SP where Q is the mass flow rate. This was found to be 316 kg/s. Because the vacuum was relatively low, the pump application chart indicated that a rotary vacuum pump would be the best for this application. The power of the pump was obtained using the Elmo Rietschle Company's power-vacuum curve and was found to be 0.6kW. The power of the pump depends of the manufacturer and so a pump of the same capacity by a different manufacturer would have a different value of power.

6 Conclusions

The objective of this project was to design a machine that crushed fluorescent lamps to release the mercury vapour in them, and to direct this vapour to an activated carbon filter for adsorption. To do this, the crusher was divided into four components: The activated carbon filter, the storage unit, the crusher unit and the vacuum pump. Each of these was analysed in turn. Data used in the analysis was obtained from various sources. The Anti-Counterfeit Agency was selected as the site because it was in possession of three shipping containers of bulbs that it had no way of disposing legally and in an environmentally safe manner. Therefore, design of this machine presents a direct solution to the Agency's problem.

6.1 Recommendations

Some studies show that the application of heat may increase the amount of mercury vapour released from the crushed bulbs since a majority of the mercury in bulbs in solid form (Jang et al, 2005). Further designs may therefore incorporate heat into the lamp crushing process.

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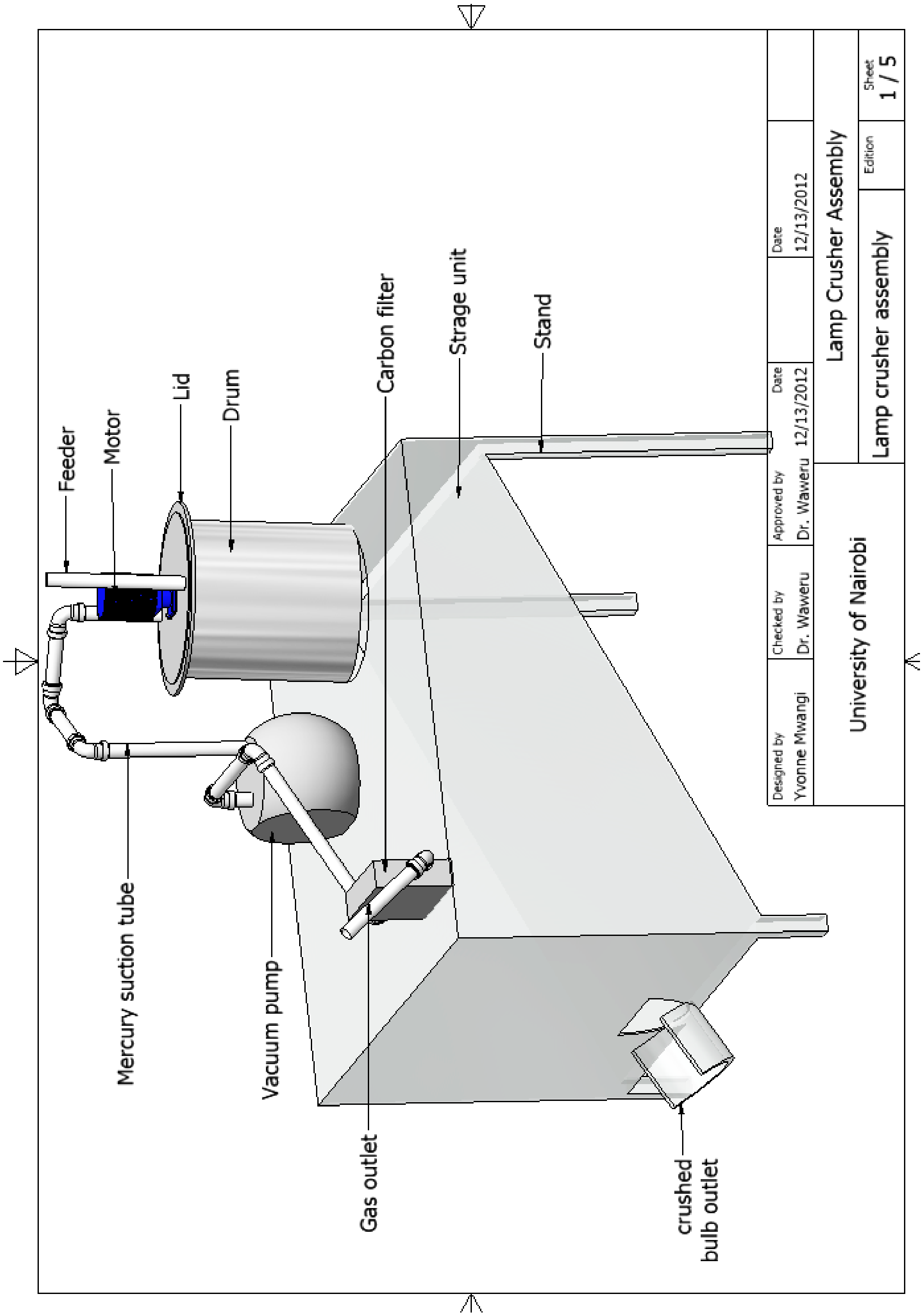
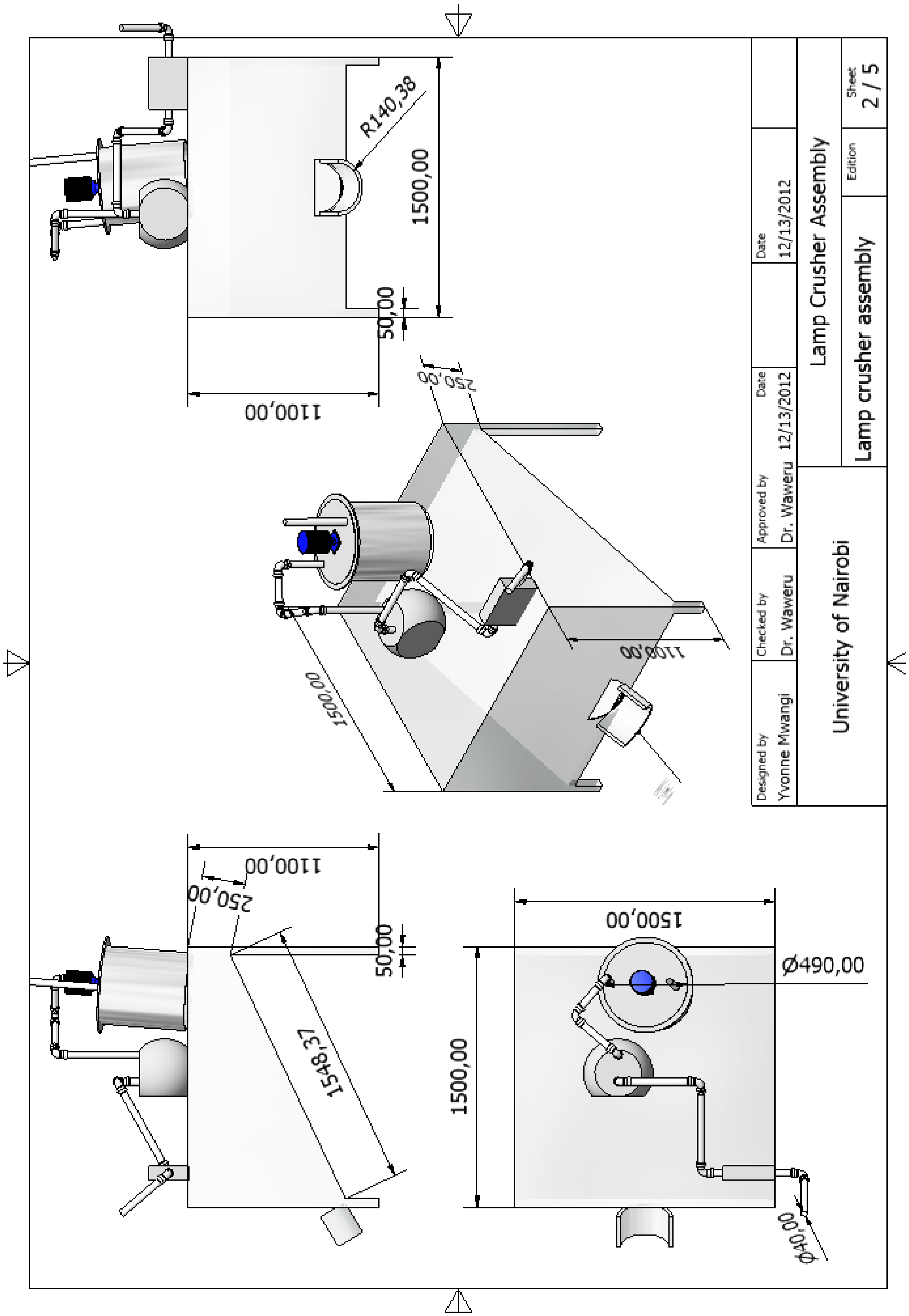
8 Appendices

8.1 Appendix 1: Design Drawings

8.1.1 The Lamp Crusher

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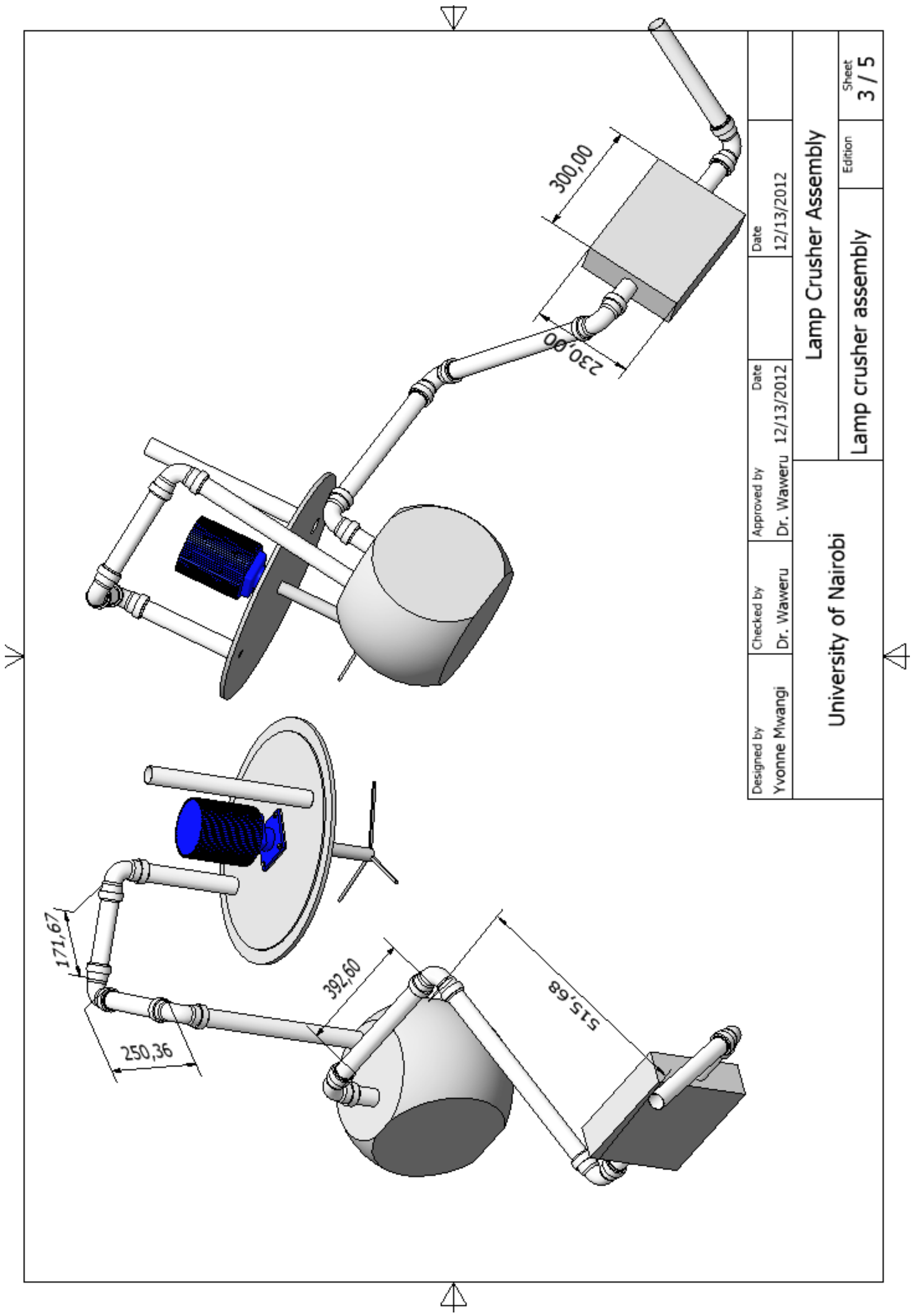
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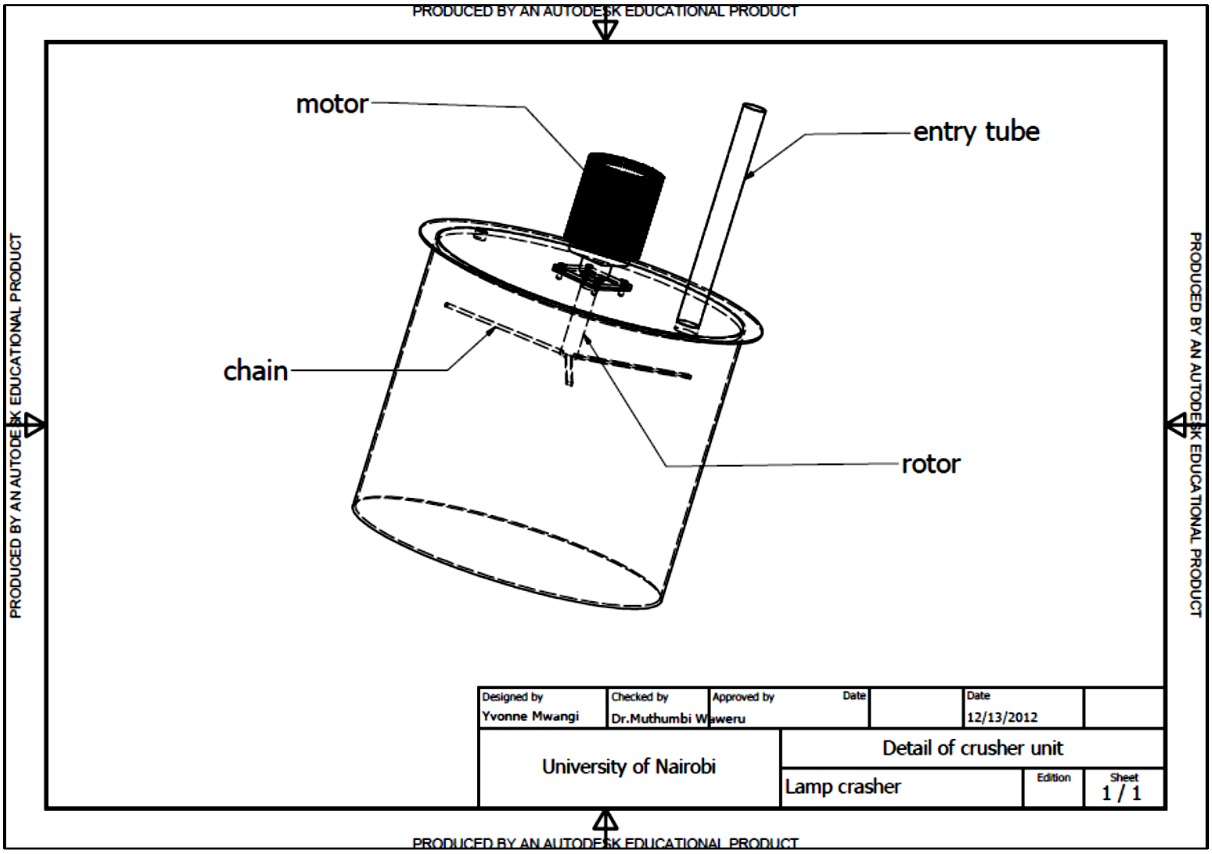
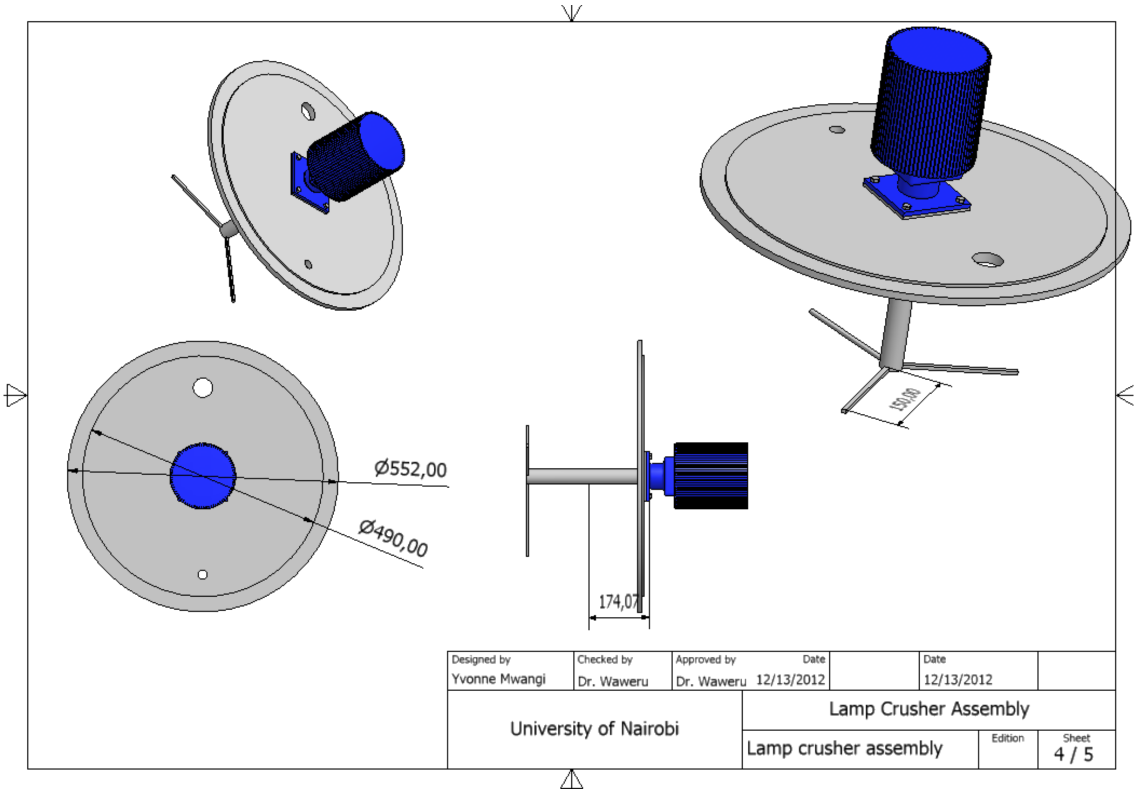
8.1.2 Crusher Unit

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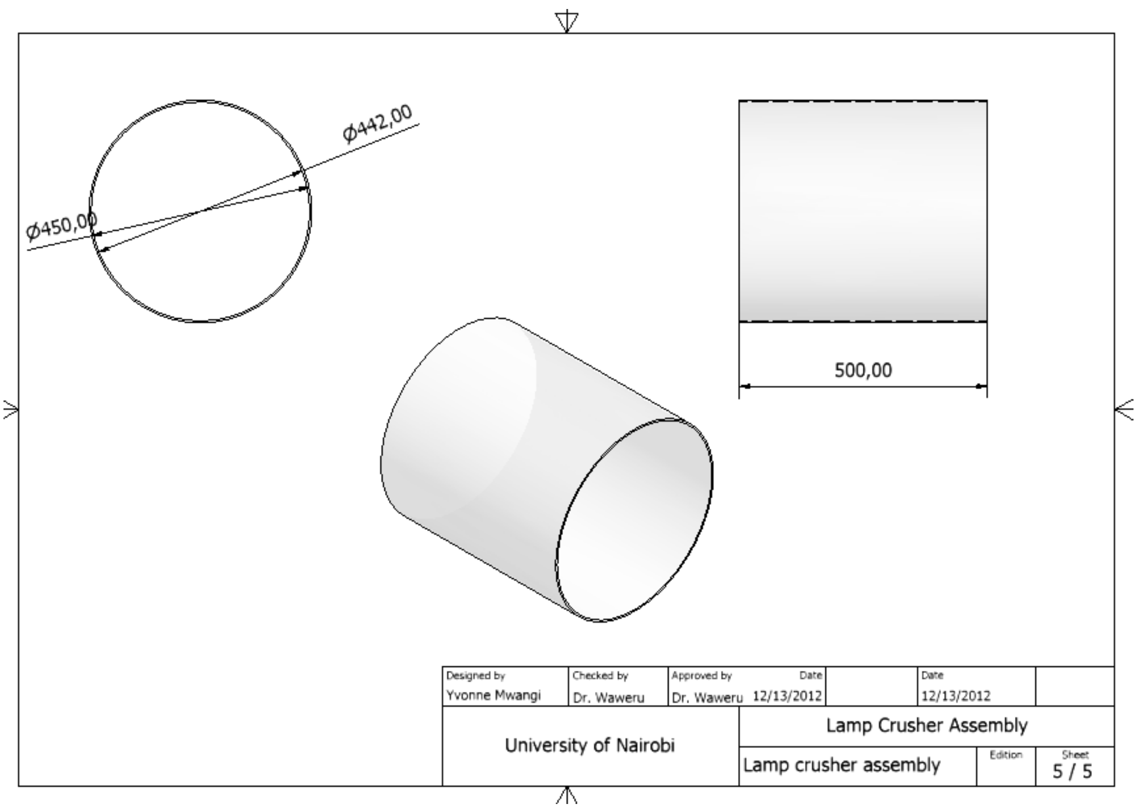
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8.2 Appendix 2 Design Calculations

8.2.1 Activated carbon adsorption analysis

Activated carbon typically sorbs 10 to 20 percent of its weight according to The Off-Gas Treatment Technologies for Soil Vapor Extraction Systems: State of the Practice manual chapter on Adsorption technologies (2006). This is its adsorption capacity, that is, the amount of the contaminant that can be adsorbed on a unit weight of activated carbon consumed at the conditions present in the application.

Therefore using 10 kg of Activated carbon, and taking 15%, its adsorptive capacity would be:

$$\frac{15}{100} \times 10 = 1.5kg = 1500g$$

Mercury content per bulb

Now a typical fluorescent bulb discarded today is likely to contain an average of approximately 20 mg mercury (Environment Canada, 2001) where the mercury in vapour form is between 17 and 40% (Aucott, 2004).

Using a mercury vapour content of 30% in a 4-foot lamp with containing 20mg of mercury, then the mass of mercury vapour would be:

$$\frac{30}{100} \times 20 = 6mg = 0.006g$$

The number of bulbs required to saturate the activated carbon will be given by:

$$\frac{Adsorptive\ capacity\ of\ Activated\ Carbon\ (g)}{mass\ of\ mercury\ vapour\ per\ bulb\ (g)}$$

$$\frac{1500}{0.006} = 250000\ bulbs$$

Time before activated carbon reaches saturation capacity

This is important to know because it gives the replacement schedule for the activated carbon

Now, if the bulbs are being fed at a rate of 15 bulbs per minute then the amount of mercury entering the system every minute is:

$$m = R \times M$$

Where m = mass of activated carbon entering the system per minute
R= rate of feeding bulbs
M= mass of Hg vapour per bulb

$$m = 15 \times 0.008 = 0.12\ g/min$$

In grams of mercury per second:

$$m = \frac{0.12}{60} = 0.002\ g/second$$

So to saturate the carbon at this mass flow rate would take time, t:

In hours:

$$t = \frac{saturation\ capacity\ of\ activated\ carbon\ (g)}{mass\ flow\ rate\ (\frac{g}{s})}$$

$$t = \frac{1500\ (g)}{0.002\ (\frac{g}{s})} = 750000\ seconds = 208.33\ hours$$

In days:

$$t = \frac{208.333\ hours}{24\ hours/day} = 8.68\ days$$

Working 8 hours a day:

$$t = \frac{208.333\ hours}{8\ hours/day} \approx \mathbf{26\ days}$$

Thus the activated carbon would need to be replaced every 26 days, or slightly earlier.

Time taken to crush the lamps at the site

Referring to Table 4, there were 3 shipping containers of lamps weighing between 30 and 35 tonnes and with a capacity of 67 m^3.

Number of lamps crushed per day:

$$= \frac{No. of\ lamps\ needed\ to\ saturate\ the\ carbon}{no. of\ days\ needed\ for\ carbon\ to\ get\ saturated} = \frac{25000}{26}$$

$$= 9615.38\ lamps\ per\ day$$

From Table 5 below, each 4-foot lamp weighs 0.3125 kg.

Table 5: Masses of different lamp types (Source: Environment Canada)

LAMP TYPE	WEIGHT (kilograms)
4/ft. fluorescent	0.3125 kg
8/ft. fluorescent	0.625 kg
H.I.D.	0.220 kg
High Pressure Sodium	0.220 kg

Each of the transport containers weighs approximately 35,000kg

Using the relative volumes therefore, the number of lamps per container was estimated as:

$$= \frac{volume\ of\ container}{volume\ of\ one\ lamp}$$

$$= \frac{67.6}{6.1778 \times 10^{-4}} = 109424\ lamps \approx 109000\ lamps$$

Time taken process all the lamps in one container:

$$= \frac{number\ of\ lamps\ per\ container}{number\ of\ lamps\ crushed\ per\ day}$$

$$= \frac{109000}{9615.38} = 11.3\ \approx \mathbf{12\ days}$$

For all 3 containers, the total time taken to crush and capture mercury vapour from the lamps would be just over a month. 12×3 =36 days

8.2.2 Storage Unit sizing

The storage unit is where the debris from crushing falls whilst the mercury-laden air is drawn into the activated carbon filter. The crushed glass, phosphor and metal end caps are stored for a time before being collected for disposal or recycling.

Volume of the storage bin:

The crusher reduces the volume 6-8 times for whole lamps (MRT Technologies)

If the lamps were to be processed in convenient batches, say 10000 lamps per batch, the volume of the full storage unit would be:

Volume of 10000 4-foot T8 lamps =

$$= \pi \frac{d^2}{4}.l$$

Where d= diameter of the bulbs

l= length of the bulbs

Diameter, d = 1 inch ≈ 2.54cm = 0.0254m

Length of bulbs, l = 4 feet = 1.2192m

Then volume of 1 bulb:

$$= \pi \frac{0.0254^2}{4}.1.2192 = 6.1778 \times 10^{-4}\, m^3$$

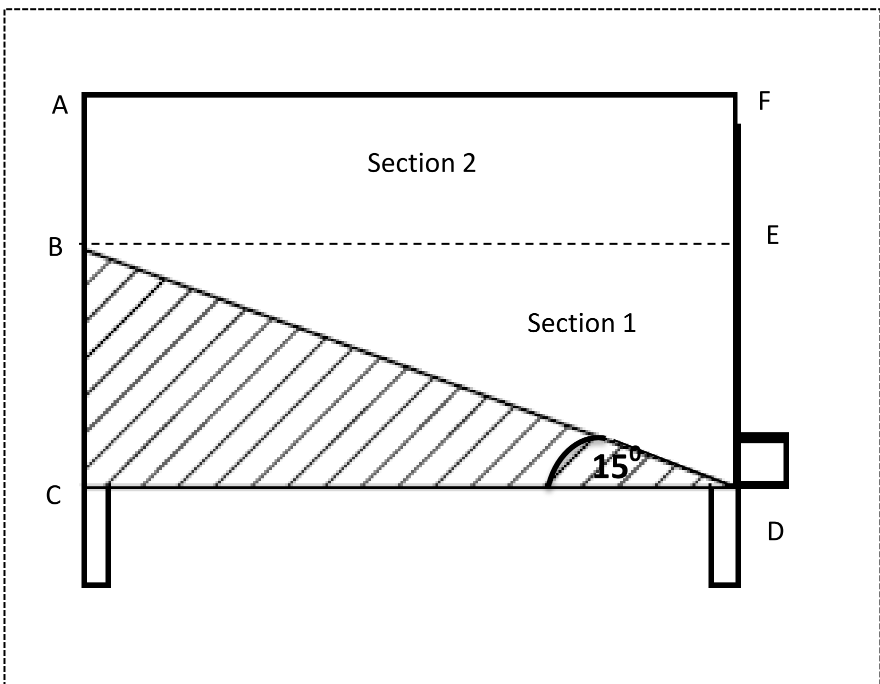
Volume of 10,000 bulbs:

$$6.1778 \times 10^{-4} \times 10000 = 6.1778\, m^3$$

However, crushing of the lamps reduces its volume 6-8 times: Taking a factor of 6, then the required volume of the containment structure would be:

$$\frac{6.1778}{6} = \mathbf{1.03\, m^3}$$

Determination of storage unit dimensions



Referring to the figure above, the cross-sectional area of the storage unit was divided into two sections: Section 1 (Triangle BED) and Section 2 (Rectangle ABEF)

If length (AF=BE) = 2m

width = 1m

Let the slope of floor of storage unit be 15^0

The height of imaginary triangle BCD would be BC = DE:

$$Tan\ 15 = \frac{x}{2} = 0.536\ m$$

So the volume of Section 1 is:

$$V1 = \frac{1}{2} bh.width$$

$$V1 = \frac{1}{2} ED \times BE \times width = \frac{1}{2} 2 \times 0.536. \times 1 = 0.536 m^3$$

The required storage volume was $1.03m^3$ and the volume of Section 1 was $0.536m^3$. Thus section two represented the remaining required volume:

i.e.

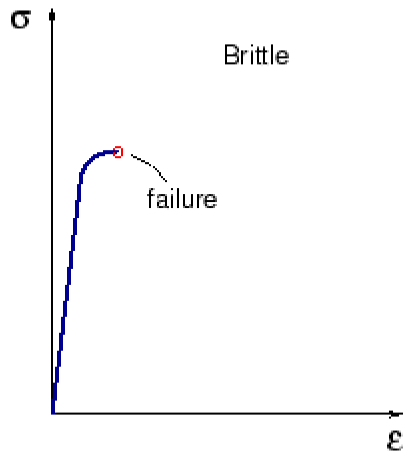
$$V2 = 1.03 - 0.536 = 0.494 m^3$$

To get the height AB of Section 1:

$$H = \frac{Volume\ V2}{LW} = \frac{0.494}{2 \times 1} = 0.247 m$$

8.2.1 Motor sizing

Because glass is a brittle material, it's yield point is taken as its ultimate maximum stress.



The yield strength of glass = 70,000 N/m^2 according to CamGlass UK glass material properties table **(**Appendix 3). Now, stress is force over area, therefore to get the force required to break the glass, we say:

$$F = \sigma \times A$$

Area is the cross-sectional area of the bulb given by:

$$A = \frac{\pi}{4}(D^2 - d^2)$$

Where: D, outer diameter =

D= inner diameter =

The glass thickness was 0.65mm (Wachtman, 2010).

So, the force required to break the glass is:

$$F = 70000 \times 5.054 \times 10^{-5} = 3.538\, N$$

The torque of the spinning chains would therefore be:

$$T = F \times d$$

Where d, length of one chain = 0.3m

Thus:

$$T = 3.538 \times 0.3 = 1.0613\, Nm$$

This represents the load torque we require from our motor. Torque of a motor can be related to the synchronous speed on a curve. By ICE standards, at the full-load torque, speed is usually 97% of the synchronous (no load) speed.

The synchronous speed of an induction motor is based on the supply frequency and the number of poles in the motor winding and can be expressed as:

$$\omega = 2 \cdot 60 \cdot f / n$$

where

ω = pump shaft rotational speed (rev/min, rpm)
f = frequency (Hz, cycles/sec)
n = number of poles

The rotational speed at different frequencies and number of poles can be listed as:

	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**
60-cycles	3600	1800	1200	900	720	600	514	450	400
50-cycles	3000	1500	1000	750	600	500	428	375	334

Motors designed for 60 Hz are common in U.S. Outside U.S Motors designed for 50 Hz are common. This is the case in Kenya (US DOC, 2002) Also, it is important to note that the most common motors are 2 pole pairs for 3000r/min and 4 pole pairs for 1500 r/min.

Therefore, taking a 50HZ, 4-pole motor, the synchronous speed would be 1500rpm.

The power of the motor in Kw:

$P = T\omega$

$P = 1.0613 \times (0.97 \times 1500)$= 1.5443 Kw

Electric motors are one of the main consumers of energy. By the IEC standard IE 60034-30 (Appendix 3), There are three levels of efficiency relevant:

IE1 - effectively low efficiency, but the vast majority of motors in use today meet this standard.
IE2 - higher efficiency, previously known as Eff1, this level will be compulsory for all new motors in Europe from 2011.
IE3 - a higher efficiency level to be introduced in 2015. As an alternative IE2 motors with frequency inverters can be used.

From the table (Appendix 3) the next highest motor in terms of rating is 2.2kW (3hp). But we must verify if that motor can supply the required power. Standard efficiency for the 4-pole, 2.2kW motor is 81.5%. This means that the actual power (shaft power) of the motor is:

$$P = 0.815 \times 2.2 = 2.0374\ kW$$

Thus this motor is suitable as it can easily deliver the 1.5kW of calculated power.

8.2.2 Vacuum Pump

The vacuum pump was sized for the required pressure using by rearranging the evacuation time equation

$$t = \frac{V}{S}\ln(\frac{P_0}{P_1})$$

such that S (Pump capacity) became the subject:

$$S = \frac{V}{t}\ln(\frac{P_0}{P_1})$$

Now, for a vacuum of 100mbar, the final pressure P1 would work out as:

$$P1 = P0 - vacuum$$

$$P1 = 1013 - 100 = 913 mbar$$

So to get the actual suction capacity:

$$S = \frac{1.03}{1} \ln(\frac{1013}{913}) = 0.2078 \text{ m3/min} = 200 \text{ L/min}$$

Now for this capacity, the mass flow rate is:

$$Q = PS = 0.913 \times 10^5 \times \frac{0.2078}{60}$$

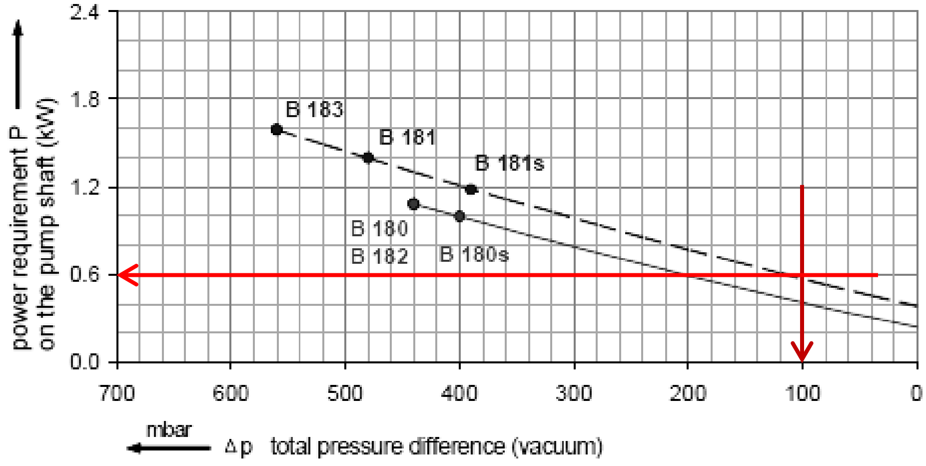
$$=316.2 \text{ kg/s}$$

Now according to the table of pressure below, 100mbar falls in the range of low vacuums. Using the pump application chart (Appendix 3), it was clear that a rotary pump would be ideal for this particular application. Rotary positive displacement pumps are in fact, the most effective for low vacuums.

Table 6 Pressure Ranges

Pressure Range	Pressure in mbar
Low vacuum	10^3 - 10^0
Medium vacuum	10^0 – 10^{-3}
High vacuum	10^{-3} - 10^{-7}
Ultra high vacuum	10^{-7} – 10^{-12}

Using the Elmo Rietschle Company's specific curves for their vacuum pumps, it was found that the power of the pump shaft at 100 mbar and operating temperature 25^0C.is 0.6 kW. However, rated power of the pump was 0.63 kW (See figure below).



(Elmo Rietschle, 2003)

8.3 Appendix 3

8.3.1 Mechanical properties of Silica Glass

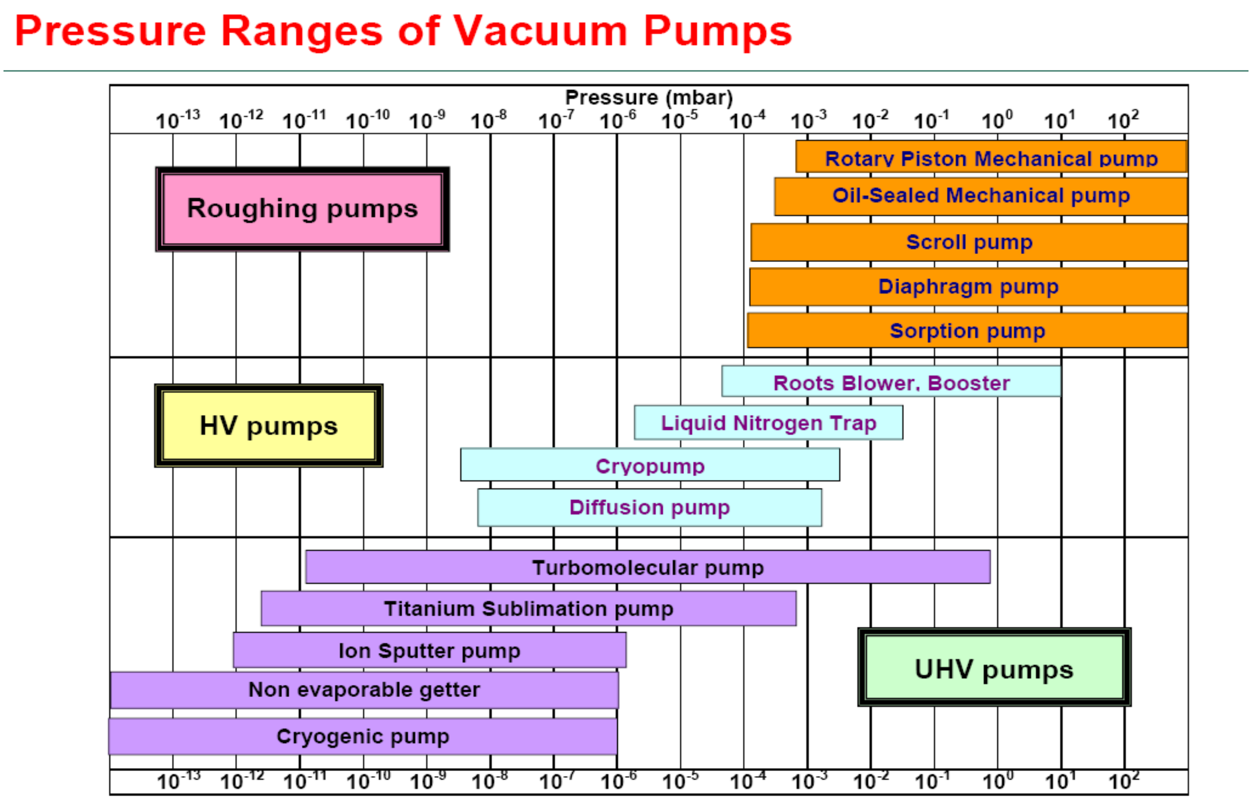
Thermal Properties	**Mechanical Properties**
Softening Point 1683°C	Density 2.20 x 103Kg/m3
Annealing Point 1215°C	Young's Modulus 74 x 106KN/m2
Strain Point 1120°C	Rigidity Modulus 32 x 106KN/m2
Continuous Operating Temp 1000°C	Compressive Strength 20 x 106KN/m2
Electrical Information	Tensile Strength 70 x 103KN/m2
Electrical Resistivity 2 x 1019 ohm cm at 20°C	Shear Strength 70 x 103KN/m2
2 x 106 ohm cm at 800°C	Mohr's Hardness 6
Dielectric Strength 10KV/mm at 20°C	**Optical**
2.5KV/mm at 500°C	Useful Optical Range Synthetic 180 –2000nm
Chemical Information	Natural 275- 2000nm
Total Metallic Impurities 10ppm (Typical)	Refractive Index nD(589 nm) – 1.458

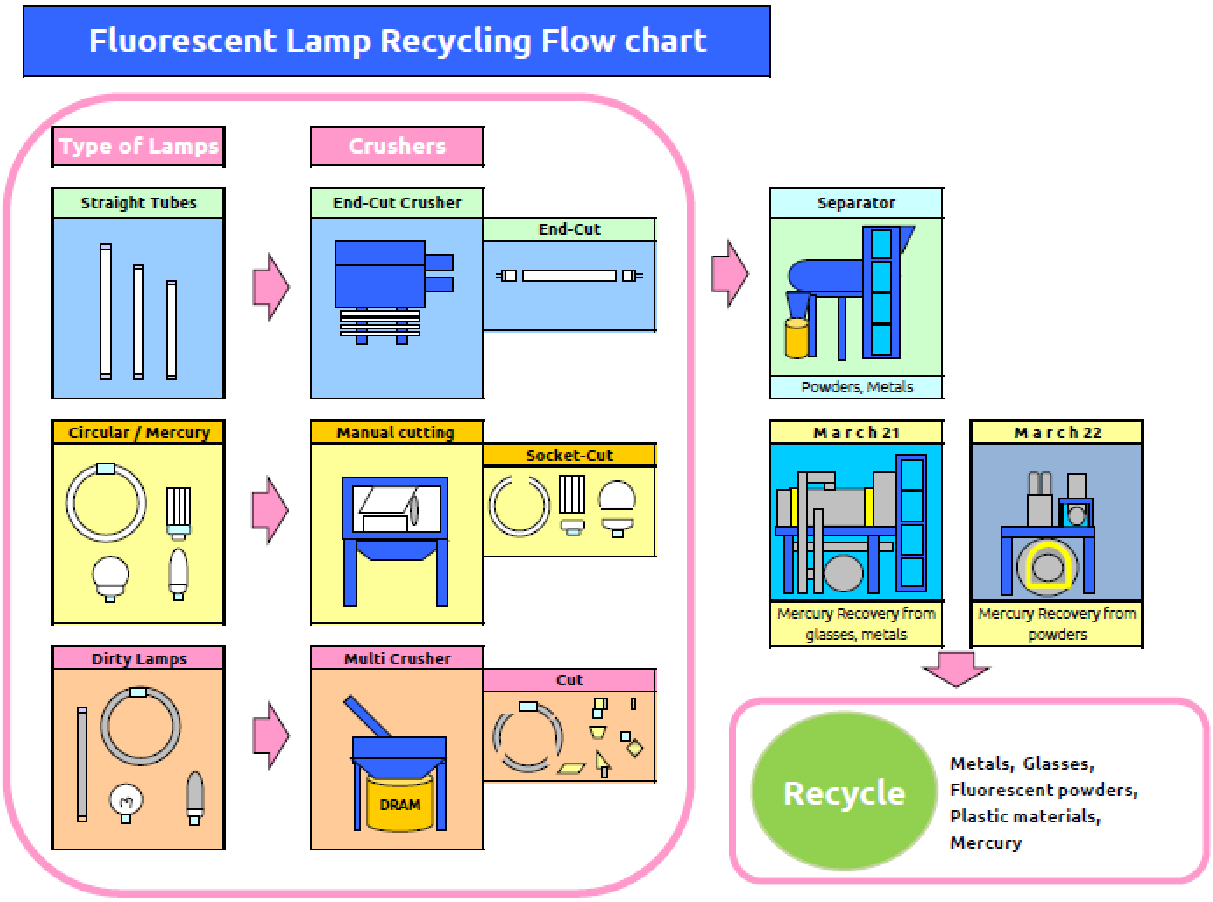
8.3.2 Motor efficiencies

Table 1 Table with efficiency classes: IE 60034-30 (2008)

kW	HP	IE-1 - Standard efficiency						IE2 - High efficiency						IE3 - Premium efficiency					
		2 pole		4 pole		6 pole		2 pole		4 pole		6 pole		2 pole		4 pole		6 pole	
		50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz
0.75	1	72.1	77.0	72.1	78.0	70.0	73.0	77.4	75.5	79.6	82.5	75.9	80.0	80.7	77.0	82.5	85.5	78.9	82.5
1.1	1.5	75.0	78.5	75.0	79.0	72.9	75.0	79.6	82.5	81.4	84.0	78.1	85.5	82.7	84.0	84.1	86.5	81.0	87.5
1.5	2	77.2	81.0	77.2	81.5	75.2	77.0	81.3	84.0	82.8	84.0	79.8	86.5	84.2	85.5	85.3	86.5	82.5	88.5
2.2	3	79.7	81.5	79.7	83.0	77.7	78.5	83.2	85.5	84.3	87.5	81.8	87.5	85.9	86.5	86.7	89.5	84.3	89.5
3		81.5	–	81.5	–	79.7	–	84.6	–	85.5	–	83.3	–	87.1	–	87.7	–	85.6	–
3.7	5	–	84.5	–	85.0	–	83.5	–	87.5	–	87.5	–	87.5	–	88.5	–	89.5	–	89.5
4		83.1	–	83.1	–	81.4		85.8	–	86.6	–	84.6	–	88.1	–	88.6	–	86.8	–
5.5	7.5	84.7	86.0	84.7	87.0	83.1	85.0	87.0	88.5	87.7	89.5	86.0	89.5	89.2	89.5	89.6	91.7	88.0	91.0
7.5	10	86.0	87.5	86.0	87.5	84.7	86.0	88.1	89.5	88.7	89.5	87.2	89.5	90.1	90.2	90.4	91.7	89.1	91.0
11	15	87.6	87.5	87.6	88.5	86.4	89.0	89.4	90.2	89.8	91.0	88.7	90.2	91.2	91.0	91.4	92.4	90.3	91.7
15	20	88.7	88.5	88.7	89.5	87.7	89.5	90.3	90.2	90.6	91.0	89.7	90.2	91.9	91.0	92.1	93.0	91.2	91.7
18.5	25	89.3	89.5	89.3	90.5	88.6	90.2	90.9	91.0	91.2	92.4	90.4	91.7	92.4	91.7	92.6	93.6	91.7	93.0
22	30	89.9	89.5	89.9	91.0	89.2	91.0	91.3	91.0	91.6	92.4	90.9	91.7	92.7	91.7	93.0	93.6	92.2	93.0
30	40	90.7	90.2	90.7	91.7	90.2	91.7	92.0	91.7	92.3	93.0	91.7	93.0	93.3	92.4	93.6	94.1	92.9	94.1
37	50	91.2	91.5	91.2	92.4	90.8	91.7	92.5	92.4	92.7	93.0	92.2	93.0	93.7	93.0	93.9	94.5	93.3	94.1
45	60	91.7	91.7	91.7	93.0	91.4	91.7	92.9	93.0	93.1	93.6	92.7	93.6	94.0	93.6	94.2	95.0	93.7	94.5
55	75	92.1	92.4	92.1	93.0	91.9	92.1	93.2	93.0	93.5	94.1	93.1	93.6	94.3	93.6	94.6	95.4	94.1	94.5
75	100	92.7	93.0	92.7	93.2	92.6	93.0	93.8	93.6	94.0	94.5	93.7	94.1	94.7	94.1	95.0	95.4	94.6	95.0
90	125	93.0	93.0	93.0	93.2	92.9	93.0	94.1	94.5	94.2	94.5	94.0	94.1	95.0	95.0	95.2	95.4	94.9	95.0
110	150	93.3	93.0	93.3	93.5	93.3	94.1	94.3	94.5	94.5	95.0	94.3	95.0	95.2	95.0	95.4	95.8	95.1	95.8
132		93.5		93.5	–	93.5	–	94.6	–	94.7	–	94.6	–	95.4		95.6	–	95.4	–
150	200	–	94.1	–	94.5	–	94.1	–	95.0	–	95.0	–	95.0	–	95.4	–	96.2		95.8
160		93.8		93.8	–	93.8	–	94.8	–	94.9	–	94.8	–	95.6	–	95.8	–	95.6	–
185	250	–	94.1	–	94.5	–	94.1	–	95.4	–	95.4	–	95.0	–	95.8	–	96.2	–	95.8
200		94.0	–	94.0	–	94.0	–	95.0	–	95.1	–	95.0	–	95.8	–	96.0	–	95.8	–
220	300	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
250	350	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
300	400	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
330	450	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
375	500	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8

8.3.3 Pressure Ranges of Vacuum Pumps





The Lamp Recycling process of the Japanese Fluorescent Lamp Company, Ltd.