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Chapter 12

Entrepreneurship and Product Design in Chemical Engineering Education

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12.1 INTRODUCTION

The purpose of this chapter is to share our experience in teaching Chemical Engineering students in Hong Kong the basic elements of successful entrepreneurship and product design through the final year design project. Chemical Engineering is a young profession in Hong Kong with the baccalaureate degree program established in 1993. Despite the lack of traditional chemical industries in Hong Kong, graduates easily find a career in many chemical-related industries and businesses including food and beverage, textiles and clothing, pharmaceuticals and electronics. However, most of these industries emphasize on product rather than process, therefore a good background in product-oriented design is a must. The proximity to inexpensive labor and growing consumer market in China give our students the unprecedented opportunity to establish their own business and enterprise. A basic training in entrepreneurship will be invaluable. Indeed, several alumni had successfully started their own chemical business and manufacturing plant in China.
12.2 BACKGROUND

12.2.1 Geographical, Historical and Cultural Background of Hong Kong

Hong Kong is located east of the Pearl River delta in the province of Guangzhou in southern China. Hong Kong consists of the Hong Kong Island, the Kowloon peninsula, New Territories and the outlying inhabited islands of Lantau and Lamma and hundreds of smaller uninhabited islets. Hong Kong became a British colony in 1842 [1]. Blessed with one of the best natural harbors in the world, Hong Kong became a trading entrepot for Chinese tea, silk and porcelain to England. Today, this legacy made Hong Kong into a vibrant commercial city that adheres closely to the principle of laissez faire. 2001 Census showed that ninety five percent of the 6.9 M Hong Kong citizens are of Chinese descent [2]. This gave Hong Kong her distinct eastern tradition and western outlook.

After liberation by the British Army at the end of World War II, Hong Kong had seen influx of immigrants from China, mostly from cities such as Guangdong, Shanghai and Nanking. A great number of the new immigrants were entrepreneurs, banker, financiers, manufacturers and skilled technicians. Their technical know-how, managerial skill and investment savvy transformed Hong Kong in less than a decade into an important manufacturing and trading center in eastern Asia. Textiles, garments, plastics, toys, household appliances and electronics were manufactured and exported. Hong Kong’s financial and banking sector also grew with the influx of capitals. The increase in labor and land costs saw the decline of labor-intensive manufacturing in Hong Kong in the late 1970. This and the liberalization of Chinese economy were responsible for the massive relocation of manufacturing facilities to China [1], mostly around the Pearl River delta (Fig. 12.2-1). For the past two decades starting from 1980, the contribution of manufacturing to the overall economy and labor market shrank by eighty percent as shown in Fig. 12.2-2. Today, manufacturing contributes to less than four percent of Hong Kong GDP and employs less than eight percent of the total labor force. Despite the rapid de-industrialization, the overall economy grew by almost forty percent during the ten years period between 1993 and 2002, because of healthy growth in the service sector particularly in the banking, finance, logistic, telecommunication and information technology. This helped alleviate the lost in manufacturing jobs. However the past few years, globalization had eroded Hong Kong’s service industry, especially the telecommunication and I.T. sectors. More recently, banking, finance and insurance companies were moving some of their operations to China and India for their cheaper labor. It is imperative for Hong Kong to transform itself into a knowledge-based economy in order not only to survive but also thrive in the decades to come.
Figure 12.2-1. Industrial development around Pearl River Delta region of Southern China.

Figure 12.2-2. Manufacturing contribution to (a) overall GDP and (b) total work force in Hong Kong [2]
The chemical engineering profession maintains a small but visible presence in Hong Kong. The Hong Kong Institution of Engineers (HKIE) registered thirty chartered chemical engineers and ninety-three chartered gas engineers. It is estimated that there are about 3000-5000 trained chemical engineers in Hong Kong. The lack of natural resources and high cost of land preclude the construction of large chemical and petrochemical plants in Hong Kong, instead small and medium scale fuel and gas processing plants supplied the local needs. There are more than eleven hundreds chemical and plastic companies and businesses in Hong Kong employing roughly fifteen thousand peoples [3]. Many chemical engineers are employed in local utility companies responsible for Towngas production, electricity generation and water and wastewater treatments. Others contribute to the growth of the local textile and electronic industries that accounts for a third of the employment in manufacturing sector. Chemical engineers are heavily involved in the modernization and mass production of traditional Chinese medicine, food and beverages. Table 12.2-1 summarizes the 2003 data on chemical-related industries and businesses in Hong Kong. An increasing number of chemical engineers are employed in local and multi-national companies with production facilities in China. It is expected that greater demand for chemical engineer will follow upon completion of several major refineries and chemical plants in neighboring Chinese provinces of Guangdong, Guangxi and Fujien.

Table 12.2-1. Chemical-related industries and businesses in Hong Kong [3]

| Commodity and Products                  | Number of Establishments | Workforce | Number of Establishments | Workforce |
|-----------------------------------------|--------------------------|-----------|--------------------------|-----------|
| Alcoholic drinks                        | 22                       | 4011      | 499                      | 3031      |
| Clothing, footwear and allied products  | 3063                     | 47580     | 20537                    | 116381    |
| Consumer goods                          | 1804                     | 8886      | 31195                    | 148627    |
| Durable goods                           | 494                      | 3309      | 11985                    | 79926     |
| Foodstuffs                              | 632                      | 24853     | 3965                     | 17650     |
| Fuel                                    | 3                        | 160       | 202                      | 1897      |
| General Commodities                     | 4059                     | 37196     | 4600                     | 18886     |
| Machinery, equipment and parts           | 2480                     | 26362     | 4461                     | 19409     |
| Raw materials and semi-manufactures     | 3716                     | 25449     | 18116                    | 81631     |
| Transport equipment                     | 429                      | 9891      | 1274                     | 5262      |
| Total                                   | 16702                    | 187967    | 99834                    | 490700    |
12.2.3 Chemical Engineering Education in Hong Kong

The Hong Kong University of Science and Technology (HKUST) is the only university in Hong Kong that offers a formal Chemical Engineering education. HKUST was conceived by the Hong Kong Governor Sir Edward Youde and Honorable Dr. Sze-Yue Chung to help propel Hong Kong towards a knowledge-based economy by training the next generation of scientists, engineers and entrepreneur how to create and not replicate. The Chemical Engineering department started accepting students in 1993, two years after the University opened its door to students in 1991. The Chemical Engineering undergraduate degree programs are accredited by the Institute of Chemical Engineers (IChemE) of U.K. and the Hong Kong Institution of Engineers. The latter is a signatory to the Washington Accord and therefore all engineering degrees accredited by the HKIE are recognized by the other signatories. Chemical Engineering education faces unique challenges and opportunities in Hong Kong. The lack of traditional chemical industries and the rapid pace of de-industrialization bring into question the relevance of traditional Chemical Engineering curriculum in Hong Kong. The emphasis of chemical businesses in Hong Kong is on product design and development as well as their manufacture. To be successful, basic business and managerial trainings are a must. New undergraduate course on Products and Processes (CENG 103), as well as language (Lang 001, 002 and 003) and professional development (CENG 001 and 002) courses were introduced. Practical industrial training, computational modeling and simulation, laboratory experimentation and research are important part of the curriculum. Department’s participation in the School-level high tech entrepreneur project (HTEP) brought together the important elements of entrepreneurship training, product design and process development in an interdisciplinary environment.

Two undergraduate programs, Chemical and Environmental Engineering (CEEV) and Chemical and Bioproduct Engineering (CBPE), were launched to train students in two emerging industries in Hong Kong. Greater environmental awareness and stricter government regulations motivate manufacturers to develop efficient and green processes and take greater responsibility in environmental management. Besides Chemical Engineering training, CEEV students learn green processes, environmental management, pollution monitoring and abatement. This combined degree enables students to understand various industrial processes and realize where environmental control measures can be implemented, thus making the community a better place to live in. Healthy growth in the local food and beverage industries, increasing demand for new health and personal care products, and advances in life sciences (i.e., pharmaceutical, genetic engineering, bio-MEMs and nanomedicines) are the reasons behind Chemical and Bioproducts Engineering. The program teaches the fundamental principles of chemical engineering along with the new
approaches from biology, biochemistry, cell biology and pharmaceutical engineering. Students are trained to use this knowledge for the design and manufacture of bioproducts and biodevices.

Figure 12.2-3 shows that most of the Chemical Engineering graduates found employment in chemical-related manufacturing and service industries. Figure 12.2-3a shows that Hong Kong chemical industries although small compared to other countries are still very much affected by the cyclical trend in worldwide chemical market. In recent years, a growing number of our Chemical Engineering graduates pursued further studies in response to the recent downturn, and growing industry demand for Engineers with Masters or Ph.D. qualifications. Figure 12.2-3b shows the latest distribution of Chemical Engineering graduates according to employment sectors. Over eighty percent of the graduates were employed within six months of finishing their studies.

12.2.4 High Tech Entrepreneurial Program (HTEP)

The six credits, Engineering school-level HTEP courses (ENG 251 and ENGG 252) were designed by Professors Mitchel M. Tseng and Phil Choong of the Department of Industrial Engineering and Engineering Management (IEEM) at HKUST for final year engineering undergraduate students in lieu of the traditional final year project. The program aims to nurture the entrepreneurial spirits of young engineers and to provide them with an enriching entrepreneurial education. The program allows the students to propose, design and develop engineering products, as well as the opportunity to experience the process of applying for patent, writing business plan and marketing a product. The ultimate goal is to teach the students how to transform an engineering idea into a marketable product. Table 12.2-2 lists the content of the HTEP course lecture.

The program was first launched in Fall 2001 with nine projects and the participation of three engineering departments. Two Chemical Engineering students helped an IEEM-led team in developing a new desiccant formulation for their proposed dehumidifier appliance. Permission was granted by the Department of Chemical Engineering following consultation with IChemE Accreditation Board for substitution of traditional FYP by HTEP for the school year of 2002-2003 with the conditions that key features of chemical engineering design were kept. Table 12.3-1 summarizes the timeline for the HTEP and FYP courses as well as the HTEP research project schedule. The table also shows how the project was designed to satisfy both HTEP and chemical engineering design requirements.
Figure 12.2-3. (a) Percent of Chemical Engineering graduates employed in chemical-related manufacturing and service industries in Hong Kong. The figure also shows the growth in the number of graduates pursuing further educations. (b) Latest data on the distribution of Chemical Engineering graduates by employment sectors.
Table 12.2-2. HTEP course content

- Background of Entrepreneurship
- Value Identification
  - Porter’s five forces
  - Competitive Analysis
  - SWOT Analysis
- Business Model
  - What is your business?
  - Mission and goal
  - How to run the business
  - Revenue mechanism
- High-Tech Entrepreneurship
  - Role of HKUST R&D Corporation Ltd
  - HKUST Venture Capital Fund
- Business Plan
  - Outline
    - Executive Summary
    - Business Opportunity
    - Technology Base
    - The Team
    - Strategic Plan
    - Financials
- Company Law
  - Fundamentals Legal Aspects of a Company
  - Memorandum and Articles of Association
- Business Niche Discovery
- Corporate Finance Basics
  - Financials Statements
- High-Tech Marketing
  - Innovators
  - Early Adopters
  - Early Majority
  - Late Majority
  - Laggards
- Patents and Intellectual Property
- Negotiation
  - Identify negotiation
  - Prepare negotiation
  - Negotiation strategies
  - Useful tactics

12.3 PROJECT DESCRIPTION

Poor air quality affects people’s health and its human and economic costs are well recognized. People spent more than eighty percent of their time indoor therefore it is imperative to maintain a good indoor air quality. The quality of indoor air is closely related to indoor activities, building construction, ventilation, furnishing materials and quality of outdoor air. Dust, particulates allergens and airborne microorganisms along with gaseous pollutants such as carbon monoxide, formaldehyde and VOCs are common indoor air pollutants. In crowded cities like Hong Kong, ventilation only aggravates the situation by bringing road-side pollutions indoor. This project challenges the student to develop an effective and inexpensive indoor air quality control appliance based on catalyst and adsorbent technologies. The product must be able to remedy
three types of pollutants: (1) dust and particulates, (2) airborne microorganisms and (3) gaseous pollutants (i.e., carbon monoxide and VOCs) associated with odors. These pollutants were selected because of their adverse health impact and their removal can be immediately appreciated by the consumer.

### 12.4 HTEP TEAM ORGANIZATION

#### 12.4.1 Team Organization and Resource

Eight final year undergraduate students from both Chemical Engineering and Chemical and Environmental Engineering programs (Table 12.4-1) were recruited for the project. Students were asked to form four teams, one for each major task identified for the project. Each team was assigned a postgraduate student mentor to oversee the day-to-day operation. A student project leader was elected every two months to take responsibility of coordinating the team, conducting progress assessment, overseeing the project’s budget expenditure and scheduling regular meetings and reports. One undergraduate student from the School of Business was recruited to help in the market survey and business plan writing. Other undergraduate students joined towards the end of the project to help the team in prototype testing.

![Table 12.3-1. Schedule of 2002-2003 HTEP](image)
A panel of experts from academia and industry (Table 12.4-2) was assembled to provide the students with professional advice. The HKUST central facilities for Material Characterization and Preparation Facility (MCPF) and Advanced Engineering Material Facility (AEMF) and the laboratories of Department of Chemical Engineering, Department of Industrial Engineering and Engineering Management, Department of Mechanical Engineering and Advanced Technology Center play a pivotal role in the success of the project. Table 12.4-3 lists the equipment used by the students in this project.

The students find the following Chemical Engineering undergraduate courses listed in Table 12.4-4 relevant to the project. The students audited several courses including the post-graduate courses, Theory and Practice in Heterogeneous Catalysis (CENG 511) and Measurements of Air Pollutants (CENG 531). The prototype design team attended the CAD/CAM course (MECH 251) of the Mechanical Engineering Department.
Table 12.4-2. Team of experts

| Name/Affiliation                                      | Expert Advice                                           |
|-------------------------------------------------------|---------------------------------------------------------|
| Prof. Ming FANG Institute for Environment and Sustainable Development, HKUST | Pollution measurements and abatements                   |
| Prof. David C. W. Hui Chemical Engineering, HKUST    | Pinch analysis, system optimization                      |
| Dr. Arthur P. S. LAU Applied Technology Center, HKUST | Bioaerosol measurements                                  |
| Mr. Victor LO Vice President, Honeywell Hong Kong     | Home appliance market                                    |
| Mr. Anthony NG Ka Hang Engineer, Honeywell Hong Kong  | Prototype design and construction                        |
| Mr. King Lun TO Applied Technology Center, HKUST       | Air sampling and VOC measurements                        |
| Prof. Mitchell M. Tseng Industrial Engineering and Engineering Management, HKUST | Mass customization, product design and manufacture       |
| Mr. Eddy WU General Manager, Chiaphua Industries Ltd. | Appliance design, costing and manufacture                |

Table 12.4-3. Research facilities and equipment

| Facility                                      | Analysis                                      | Access | Cost |
|-----------------------------------------------|-----------------------------------------------|--------|------|
| **Advanced Engineering Materials Facility (AEMF)** |                                             |        |      |
| Nitrogen physisorption Coulter SA 3100        | BET surface area and pore size distribution   | TRAINED| FREE |
| Oven and fume hood                           | Adsorbed and catalytical calculation           | TRAINED| FREE |
| Zeta potential meter                         | Surface Zeta potential and particle size distribution | TRAINED| FREE |
| **Advanced Technology Center (ATC)**         |                                             |        |      |
| Aerosol sampler Dust Track and Monitoring (Model 8520) | Airborne particulate size and counts           | TRAINED| FREE |
| Bioaerosol sampler SMC Bioaerosol Impactor    | Airborne bioaerosol counts                    | TRAINED| FREE |
| Thermocouple and hygrometer Cole-Parmer Thermohygrograph (DH-3765-10) | Ambient temperature and humidity               | TRAINED| FREE |
| Incubation oven                               | Bacteria and Fungi incubation                  | TRAINED| FREE |
| VOC analysis Stork Chromato Chromatograph     | Formaldehyde, ETX (benzene, toluene and xylene) | TRAINED| FREE |
| Sterilizer                                    | Sterilization of culture plates and glasswears | TRAINED| FREE |

**Department of Chemical Engineering**

| Facility                                      | Analysis                                      | Access | Cost |
|-----------------------------------------------|-----------------------------------------------|--------|------|
| Process simulation                           | Nanomaterial processing                       | TRAINED| FREE |
| Atomic force microscopy (AFM)                 | Nanoparticle size and morphology              | TRAINED| FREE |
| Gas analyzer (CO & CO2)                       | Ambient carbon monoxide and carbon dioxide level | TRAINED| FREE |
| Computational fluid dynamic simulator         | CFD simulation of indoor air flow and pollutant dispersion | TRAINED| $    |
Table 12.4-3. Research facilities and equipment – cont.-1

| Facility                                                        | Analysis                                                                 | Access     | Cost |
|----------------------------------------------------------------|-------------------------------------------------------------------------|------------|------|
| Department of Chemical Engineering (cont.)                      |                                                                         |            |      |
| Fourier transformed infrared spectroscopy (FTIR)                 | Surface chemistry, adsorbed species, reaction mechanism                  | Trained    | Free |
| Gas Analyzer: Photocatalyst Machine (Model 1302)                  | Formaldehyde, carbon monoxide, carbon dioxide                           | Trained    | Free |
| Gas Chromatography (GC)                                         | On-line reaction study, off-line sample analysis                         | Trained    | Free |
| Inductively coupled plasma, atomic emission spectrometer (ICP-MS) | Catalyst loading and bulk composition                                  | P0         | $    |
| Oven (convection, microwave, vacuum)                             | Adsorbent and catalyst preparation                                       | Trained    | Free |
| Syringe pump (Millipore 1000)                                    | VOC metering and feed                                                    | Trained    | Free |
| Temperature programmed desorption-reduction-oxidation Autosampler| Active site identification and analysis                                 | P0         | Free |
| UV-visible spectrophotometry                                    | Concentration measurements                                              | Trained    | Free |

Design & Manufacturing Services Facility

| Facility                     | Analysis                        | Access     | Cost |
|------------------------------|---------------------------------|------------|------|
| CAD/CAM Software             | Prototype design                | Trained    | Free |
| Control box                  | Temperature controller and programmable units                           | Technician | $    |
| Sensors and sensor box       | Circuit design and construction of sensor box                           | Technician | $    |

Engineering School

| Facility                      | Analysis                           | Access     | Cost |
|-------------------------------|------------------------------------|------------|------|
| Aerosol impactor             | Airborne particulate size and counts| Trained    | Free |
| Air pump                      | Air sampling                       | Trained    | Free |

Glassblowing Facility

| Facility                     | Analysis                        | Access     | Cost |
|-------------------------------|---------------------------------|------------|------|
| Glassware                    | Glassware design and fabrication| Technician | $    |

Table 12.4-3. Research facilities and equipment – cont.-2

| Facility                                                        | Analysis                                                                 | Access     | Cost |
|----------------------------------------------------------------|-------------------------------------------------------------------------|------------|------|
| Department of Industrial Engineering and Engineering Management|                                                                         |            |      |
| Rapid Prototyping                                               | Preparation of a 1:4 prototype of external casing                       | Technician | $    |

Department of Mechanical Engineering

| Facility                     | Analysis                           | Access     | Cost |
|-------------------------------|------------------------------------|------------|------|
| Air flow meter (Millipore Stack Air Monitoring (Model 8520)) | Prototype air flow measurement                           | Trained    | Free |
| Sound measurement (Noise Interacting Sound Level Meter (NLSM)) | Noise level                                       | Trained    | Free |

Material Characterization and Preparation Facility (MCPF)

| Facility                                      | Analysis                                                                 | Access     | Cost |
|-----------------------------------------------|-------------------------------------------------------------------------|------------|------|
| Electron microscopy (TEM, SEM)                | Particle size distribution, particle shape and morphology               | PG         | Free |
| Micro-Raman spectroscopy                      | Crystal phase structure, crystal size, surface metal oxide structure and coverage | Trained    | Free |
| Thermogravimetric and differential thermal analyses (Itron 331190) | Phase transition temperature                                          | Trained    | Free |
| X-ray diffraction (XRD)                       | Crystal phase structure and crystal size                                | Technican  | Free |
| X-ray photoelectron spectroscopy (XPS)        | Surface composition and oxidation states                                | Technican  | Free |
Table 12.4-4. Chemical Engineering relevant to the project

| Course Code | Course Title | Description |
|-------------|--------------|-------------|
| CENG 099   | Industrial Training | A practical training course for a total duration of about eight weeks covering electro-plating, photo-chemical etching, metal surface finishing, plastic technology practices, CAD, drawing, process instrumentation, process simulation, air pollutant measurement, and safety. |
| CENG 151   | Introduction to Materials Science and Selection | Materials fundamentals: atomic bonding, crystalline structure, imperfection, phase diagrams and kinetics. Materials: metals, ceramics, plastics and composites. Materials selection for the chemical process industries. |
| CENG 152   | Introduction to Environmental Engineering | Fundamentals of environmental engineering. Sources of pollution. Pollution problems in water, air, on land and from noise and waste energy. Global pollution. Overview of pollution prevention and minimization. |
| CENG 211   | Reaction and Reactor Engineering | Stoichiometry and reaction equilibria. Homogeneous reactions kinetics. Mole balances: batch, continuous-stirred tank and plug flow reactors. Collection and analysis of rate data. Catalytic reaction kinetics and isothermal catalytic reactor design. Diffusion effects. |
| CENG 377   | Introduction to Air Pollution Control | Introduction to absorption and adsorption, scrubbing, stripping, membrane separation, incineration, catalytic reduction, particulate removal using settling chambers, cyclones, electrostatic precipitators, filters, and wet collectors. |
| CENG 388   | Investigation Project | Students conduct in-depth experimental/computational investigations on selected topics in one of the departmental research areas. Students work under supervision and are encouraged to use their own initiative to complete an appropriate program of work within the semester. |

12.4.2 Management Tools 101

The students were taught a number of management tools essential for the efficient operation of the project [4]. These include:

12.4.2.1 Time Management
Time management is essential for the students, who had to balance their time commitment to the project and the workloads from the other courses. They were also required to take an additional six credits course in the school level, high tech entrepreneurship program (HTEP) for both Fall and Spring semesters. Each semester, the students were asked to monitor their activities for one week period, rank the activities in term of priority and calculate the amount of time used. The students were then asked to reassess their time usage and create an action plan.

12.4.2.2 Critical Path Analysis
Critical path analysis was used to identify the major tasks needed for the successful completion of the project. The team met to make the worst and best case projection for the project completion. Project tasks and subtasks were listed on separate index cards. The cards were arranged on a bulletin board in sequential orders and colored pens were used to mark the connectivity and flow of the various tasks. Different task arrangements were explored taking into account the project objectives, student training and the available time and resource for the project. The best arrangement was to subdivide the team along four semi-independent tasks. These are the indoor air quality survey needed to obtain a better understanding of indoor air pollution in Hong Kong households; design of a high capacity, regenerable VOCs adsorbent; formulation of an
efficient, low temperature oxidation catalysts to convert airborne VOCs into harmless carbon dioxide and water; and construction of a working prototype for indoor air quality control appliance based on the new adsorbent and catalyst materials.

12.4.2.3 Skill Matrix and Team Working
Skill matrix was used to assess the skills and weaknesses of the team members and help select the best team composition for each of the four major tasks identified by the critical path analysis. The process involved the whole team and started with the listing of the essential background and skills needed for each task. After grouping together related skills, the ten most important skills were selected. Individual team member then rated themselves in the scale of 1 (poor) – 5 (excellent) against each skill. The result was analyzed and discussed in a friendly and informal environment to promote honest self-assessment. Each member was also asked to rank each topic in order of preference and list three individuals that they would like to be partnered with. The final team composition was decided based on the skill matrix and individual preferences. The team working principle was used to enable the team to work more effectively together. The discussion was done to identify issues, gaps and areas for improvement within the team. The purpose is to create a good working environment and encourage teamwork.

The students used the Gantt chart to plan and monitor the project progress. Each team prepared a detailed list of tasks, milestones and deliverables. A timeline was constructed based on the completion time, delivery schedule and estimated time needed to complete each task. The Gantt chart enabled the students to identify dependency between various tasks and recognize potential bottlenecks in the project. The critical tasks, scheduled tasks, completion dates and delivery time were clearly labeled. Each week the teams met to discuss and update the Gantt chart, as old tasks were completed and new ones started.

12.4.2.4 Decision Mapping, Decision Table and Effort Impact Graph
Experienced engineers and professionals can often intuitively make the correct decision given a number of options [5], however this cannot be expected of young students. The students were taught how to use decision mapping, decision table and effort impact graph to guide their decision process. A high-level process diagram for decision mapping is illustrated in Fig. 12.4-1 [4]. The diagram clearly defined each steps of the decision process and their relationship to one another. The quality, confidence, time and cost of the decision are taken into account during the process. Decision table was then employed to select the best alternative from a number of options. This involves listing the judging criteria and their relative importance (i.e., weighing factor). Using a score of 1 (poor) – 5 (excellent), the various options were scored against the listed criteria and the overall score was used to guide the decision. It is important to note that
this decision is still far from being objective since the weightings and criteria scores are often based on subjective opinions. The effort impact chart was used to visualize the relative effort needed for each alternative options and its overall impact on the project.

![Diagram of decision map]

12.4.2.5 Brainstorming
Regular brainstorming sessions were conducted during the duration of the project involving the whole team and invited guests. Creative solutions and designs were established during these sessions. Each session dealt only with one design or process problem. Ideas are encouraged by allowing each team to pre-work the problem beforehand. The sessions were informal and freewheeling, with all ideas being welcomed. The assessment was conducted in a friendly and constructive way. Principles of pre-work and forced combination were employed to provide better structure to the brainstorming sessions.

12.5 BUSINESS PLAN

The students were asked to draft a business plan early in the project to better understand the product requirements. It served as an important guide in the product design and development. This section discusses only the main elements of the business plan.
12.5.1 Product Description and Production Strategy

The product is a household appliance designed to deliver clean air by removing and killing airborne microorganisms, and converting carbon monoxide and common VOCs found indoor into harmless carbon dioxide and water. It also dehumidifies indoor air and maintains a comfortable humidity level that suppresses fungal proliferation. The appliance is intended to maintain its performance without maintenance for at least two years and is expected to have a functional life of at least five years. The product contains an active formulation of (1) low temperature oxidation catalyst, (2) VOCs adsorbent and (c) desiccant.

An efficient, low temperature oxidation catalyst was developed based on highly disperse metal catalyst on nanostructured TiO₂ support. Addition of dopants inhibits metal sintering and prevents catalyst deactivation. The nanostructured catalyst was formulated to tolerate common poisons found in environments such as halogen- and sulfur-containing compounds. The nanocatalyst is capable of oxidizing carbon monoxide and common VOCs to carbon dioxide and water at near ambient temperatures (25-50 °C).

Chemical and structural modification of mesoporous silica produces a regenerable adsorbent with large adsorption capacity for VOCs, fast adsorption rate, excellent regenerability (i.e., lower regeneration temperature and faster regeneration) and superior hydrothermal stability than the original MCM-41. A new desiccant formulation was prepared from a mixture of submicron-sized silica gel and molecular sieves to achieve the best combination of large water capacity, rapid water adsorption and easy regenerability. The formulation also tolerates the presence of VOCs and smokes.

The team agreed that the production of (1) low temperature oxidation catalyst, (2) VOCs adsorbent and (3) desiccant should be the core business of the new enterprise and the appliance manufacture should be conducted through strategic partnerships with Chinese OEMs. The enterprise will produce the catalyst, adsorbent and desiccant in suspension, paste and powder forms as needed for their incorporation in the appliance. Honeycomb filter made of the formulated powders will also be one of the main products. The enterprise will design the appliance and provide the blueprint along with components containing the active formulation to the OEM partners. The OEM manufacturers will be responsible for the manufacture of mechanical and electrical components and their assembly into an appliance.
12.5.2 Market Analysis

The project team with the help of Mr. Eddy Wu of Chiaphua Industries Ltd. and Mr. Bobby Poon Chi Hung, an undergraduate business student, conducted a detailed market survey and analysis.

12.5.2.1 Market needs

Hong Kong is densely populated with only about 100 square kilometers of land available for residences, commerce and industries [6]. The lack of local heavy industries means that vehicular emission is the major source of city’s air pollution. Hong Kong has roughly 400,000 private vehicles and despite the government’s best efforts to reduce the pollution emission by banning the sales of leaded petrol starting April 1999 and by tightening the regulation on sulfur content of diesel fuel to 0.005 % starting from April 2002, the local Air Pollution Index (API) remained “high” for more than 300 days of the year. Notwithstanding the introduction of liquefied petroleum gas (LPG) taxi scheme by the Environment, Transport and Works Bureau in 1999 to further decrease the carbon monoxide, hydrocarbons, NOx and particulate emissions from city taxis, the number of days with “very high” API has been increasing for the past few years [7]. The proximity of Hong Kong to the heavily industrialized Pearl River Delta may be a contributing factor to the city’s worsening air pollution. Indeed, a recent study [8] shows that pollution in summer is lower when the prevailing wind comes from the South China Sea, but considerably worsened during the winter months when the wind blows from the north bringing in the pollutions from the Pearl River Delta.

Hong Kong’s population of more than seven millions people lives in less than 70 square kilometers of land [6] with most of the two million households concentrated within the two narrow strips of lands in Kowloon peninsula and Hong Kong Island that border the Victoria Harbor. A typical Hong Kong household has an average of 3.2 family members and lives in a high-rise apartment of an average size of 40 m². A medium-sized, HK apartment building houses around 200 families and poor indoor air quality is a growing concern of the residents. Many reports [9] showed that indoor air quality could be ten times worse than outdoor because of poor air ventilation. This can be vividly experienced by simply strolling down an apartment corridor, where one is assaulted with a riot of odors from cooking, incenses, smokes, deodorizers and disinfectants. Hong Kong has a humid weather with average relative humidity of about 80 % throughout the year [10]. Summer is hot and humid with a monthly rainfall of more than 300 mm. The humidity encourages the growth of fungi and mildews, those spores can triggers allergic reaction and even asthma.

Poor indoor air quality is believed to be responsible for the high number of asthmatic children in HK (10.1 %) compared to neighboring cities in the region,
and this number has been increasing over the years from 4.8 % in 1989 to 11.2 % in 1995 and 17.2 % in 2002 [11]. Other children respiratory illnesses such as rhinitis (42.4 %), nasal allergy (37.4 %) and wheezing (9.4 %) are also showing a rising trend [12]. Besides children, Hong Kong’s ageing population is also at a greater risk from respiratory diseases. Hong Kong is not a stranger to disease outbreaks. There was the bubonic plague in late 1800, the Hong Kong flu (H3N2) in 1968, the avian flu (H5N1) in 1997 and the Severe Acute Respiratory Syndrome (SARS) that occurred early March 2003 during the later part of this project. Government report suggested that poor building ventilation design played a role in the spread of SARS virus at Amoy Garden Apartment Block E where about 213 residents were infected. It was believed that aerosolized fecal matters from an infected resident were spread by ventilation to neighboring flats.

An air-cleaning appliance capable of trapping, killing and eventually mineralizing airborne microorganisms, as well as removing and converting harmful carbon monoxide, volatile organic compounds (VOCs) and odors into harmless carbon dioxide and water to deliver clean air, is therefore highly desirable.

12.5.2.2 Market Survey
Hong Kong economy was in recession from 1999 until 2003 following the Southeast Asian economic crisis. The economy suffered further downturn during and after the SARS outbreak of 2003 resulting in record high unemployment and a deflationary market, which mean lower consumer purchasing power. Unlike Japan where air cleaner is considered a common household appliance, less than 1 % of surveyed Hong Kong households owned an air cleaner. However, 93.3 % of Hong Kong families have at least one air conditioner and 56.7 % have dehumidifiers. It is therefore attractive if the technology can be implemented using either air conditioner or dehumidifier as an appliance platform. A 2-in-1 appliance would appeal to the price-conscious consumers and enables the new technology to rapidly penetrate the market. A decision was made to use the dehumidifier as a platform for the new technology.

The market survey also revealed that when buying an air cleaner, 23 % of Hong Kong consumers place high priority on the price; 19 % decide based on the appliance’s ability to remove harmful particulates and 15 % consider the ability to eliminate odor important. In purchasing a dehumidifier, the decision was made mainly based on the price (25 %) and capacity (22 %). Eighteen percent of the people surveyed would consider air-cleaning function an attractive feature for the dehumidifier. The targeted market segments are households with mid-to-high level incomes, who are best able to afford and are more willing to pay for the added air-cleaning function in their dehumidifier. The survey data in
Fig. 12.5-1 shows that Hong Kong population is ageing and becoming better educated. The middle-aged and better-educated city residents are more health conscious and should be more willing to adapt new innovative products.

**Figure 12.5-1.** Market survey of Hong Kong consumer population in term of (a) age and (b) education.
12.5.2.3 SWOT and VIRO Analyses
The SWOT and VIRO analyses shown in Tables 12.5-1 & 12.5-2 were conducted to better understand the strengths and weaknesses of the product and available resources needed for the success of the enterprise. SWOT analysis of competitors was also carried out to identify areas where the product can gain competitive advantage.

Table 12.5-1. SWOT analysis of the product.

| Strengths:                                                                 | Weaknesses:                                      |
|---------------------------------------------------------------------------|--------------------------------------------------|
| 1. Effective against the complete range of indoor air pollutants including organic- & bio-aerosols, VOCs, odors and carbon monoxide; | 1. Unable to remedy inorganic aerosols;          |
| 2. New advanced technology;                                               | 2. Low clean air delivery rate (< 100 cfm);      |
| 3. Inexpensive material;                                                  | 3. Produces carbon dioxide.                      |
| 4. Easy to manufacture.                                                  |                                                  |

| Opportunities:                                                           | Threats:                                         |
|-------------------------------------------------------------------------|--------------------------------------------------|
| 1. Large potential market and growth prospects;                         | 1. Market acceptance of new technology;           |
| 2. No product of similar performance available in the market.           | 2. Confusion between new and old technologies.    |

Table 12.5-2. VIRO analysis of the enterprise.

| Valuable:                                                               | Rare:                                            |
|------------------------------------------------------------------------|--------------------------------------------------|
| 1. Catalyst and adsorbent could be easily manufactured;                | 1. Catalyst is relatively new technology for indoor air cleaners; |
| 2. The proprietary composition is difficult to imitate.                | 2. Regenerable adsorbent is new for the industry. |

| Inimitable:                                                            | Organization (ORG):                             |
|-----------------------------------------------------------------------|--------------------------------------------------|
| 1. Protected by patents;                                               | 1. Investment money is need to setup a company;  |
| 2. Customisation for different market segment is accomplished by using different product formulations. | 2. Profit sharing with strategic partners.        |
12.5.3 Competitor Analysis

The majority of air cleaners are designed to remove dust and allergens from the air. The mechanical air cleaners use filters to trap and remove the particles from air drawn in by the appliance. They often employ medium- to high-efficiency filters that have rated efficiency between 20-60%. The filters are either disposable or reusable (i.e., washable filters). The high-efficiency filters are often mistakenly marketed as HEPA-type filter. The characteristics of true HEPA filter are summarized in Table 10. Air cleaners that employ electrostatic precipitators and ionizers to remove airborne particles are categorized as electronic air cleaners. Electrostatic precipitators use a small electrical charge to collect particles from air pulled through the device, while ionizers produce negative ions that cause airborne particles to stick to materials around the vicinity of the appliance. Table 12.5-3 lists their respective strengths and weaknesses.

Table 12.5-3. Competitor analysis – cont. 1

| Advantages                                      | Disadvantages                                      |
|------------------------------------------------|---------------------------------------------------|
| **HTEP Filter**                                  |                                                    |
| 99.97% removal efficiency for 0.3 microns particles; | Very high pressure drop;                          |
| Particle removal efficiency increases with use;  | Large fans is noisier and consumes more energy;   |
| Long maintenance-free life of up to one year, five years when used with prefilters. | Replacement filter costs between US$50 to US$100. |
| **Electrostatic Precipitator**                   |                                                    |
| Established technology for removing dust, condensable organics (e.g., oil) and cigarette smoke; | Removes at best 40-50% of larger particles (> 0.3 μm); |
| No filter to replace.                            | Requires constant maintenance;                     |
|                                                | Low clean air delivery rate.                      |
| **Ionizer**                                      |                                                    |
| Established technology for removing dust;        | Ions distribution is uncertain and unpredictable;  |
| Compact design                                   | Generates secondary pollution in form of ducts deposited around the vicinity of the appliance; |
| No filter to replace.                            | Ineffective against gaseous pollutants;           |
|                                                | Requires constant maintenance.                    |
Odors associated with gaseous pollutants are often treated by adsorption on activated carbons and charcoals. Permanganate-coated alumina is known to be also effective in removing persistent odors. Photocatalytic oxidation (PCO) using UV-irradiated TiO$_2$ catalyst is popular in Japan for treating organic air pollutants and is proven effective for smokes and odors. UV-irradiation is also known to inactivate a wide-range of bacteria, fungi, spores and viruses. Ozone air treatment devices are still popular in Asia despite the established health risks associated with this technology. A comparison of the various technologies is shown in Table 12.5-3.

It is not unusual for air cleaners to employ two or more of the technologies listed in Table 12.5-3 to achieve the desired target performance and cost. This is particularly true for most air cleaners in Asia where the design includes coarse prefilters, high-efficiency filter package, activated carbon, ionizers and often one or more unconventional technologies such as germicidal filter, PCO and air freshener. The latter is used mainly as marketing ploy. The price range of these products is from US$100 to US$ 400 depending on the technology and design.

12.5.4 Generic Competitive Strategy

The students identified the best competitive strategy for the product and company is to focus on a single market segment (Fig. 12.5-2) and avoid direct
competition with established companies that could easily afford better price and provide a larger range of products. Both product and technology being new require a different marketing approach since different people have different adoption rates with some liking new things, while others only purchase tried and tested products.

The innovators prefer buying things that are new and will be targeted through magazine advertisements and home shopping network. Product test by this group will be conducted prior to mass production in order to fine-tune the design. The students also proposed to market the product to new residential and commercial buildings with environmental design concepts through partnerships with real state developers and apartment renovators to create a group of early adopters. To reach the peoples belonging to early and late majorities, product tests and certifications by established laboratories and consumer organizations would be sought. Testimonial and print advertisement will be launched. Discounted price, rebates and refunds will be considered to attract more costumers. Partnership with retail industries will be important to reach larger costumer base.

![Diagram](image)

Figure 12.5-2. Identifying the generic competitive strategy.

### 12.5.5 Company Formation

The project team drafted and signed a “Memorandum of Association” and “Article of Association” shown in Fig. 12.5-3 & 12.5-4 establishing a “virtual” company named Gryphon Technologies Limited. The purpose of this exercise is to teach the student the basic steps and legal aspect of forming a company.
Memorandum of Association

Gryphon Tech Limited

1. The name of the company is "Gryphon Tech Limited".
2. The registered office of the company will be situated in Hong Kong.
3. The company's name may be altered if it is deemed to be in the interests of the company or the public.
4. The company's objects are for the promotion of public benefit.

Figure 12.5-3. A copy of the students' Memorandum of Association.

Articles of Association

Gryphon Tech Limited

KL Yeung

1. The Articles of Association are as follows:

---

KL Yeung

Figure 12.5-4. A copy of the students' Article of Association.
12.6 INDOOR AIR QUALITY

Poor indoor air quality is the main culprit behind sick building syndrome (SBS) that describes a host of symptoms that include headache, nausea, dizziness, sore throat, dry and itchy skin, sinus congestion, nose irritation and fatigue. It is known to triggers and exacerbates allergies and asthma. Fisk and Rosenfeld [13] estimated the total costs of poor indoor air to US firms to be about US$ 10-20 billions for sick building syndrome, US$ 1-4 billions for allergies and asthma and US$ 6-19 billions for other respiratory-related illnesses. A similar study conducted by the Hong Kong Environmental Protection Department revealed that about three percent of the salary loss is associated with poor indoor air [14], which is roughly equivalent to US$ 0.15 billions each year.

Researchers found that indoor air quality (IAQ) is closely related to indoor activities, building, ventilation and furnishing materials and quality of outdoor air. IAQ survey carried out at nine local Hong Kong shopping malls showed that high occupancy and insufficient ventilation led to high level of carbon dioxide, while illicit smoking and poor ventilation at the food courts contributed to the substantially higher carbon monoxide and PM10 levels [15]. Domestic homes in Hong Kong also registered alarmingly high level of PM10. It was confirmed by a separate study that the respirable suspended particulates (RSP) and total suspended particulates (TSP) in Hong Kong residential buildings are significantly higher than most countries [16]. This is aggravated during cooking, smoking and incense burning. The ambient air pollution level in Hong Kong follows a seasonal trend [8]. Air pollution is less during summer because the prevailing shore wind helped dilute the air pollution, while in winter, a northerly synoptic airflow carried large amount of pollutants from the neighboring industrialized areas of Southern China.

Table 12.6-1 lists the common indoor air pollutants, their sources and health impacts. Information for indoor VOCs is listed in a separate Table 12.6-2. A summary of indoor air quality standards and guidelines for different countries is presented in Table 12.6-3.
Table 12.6-1. Sources and health impacts of common indoor air pollutants.

| Indoor Air Pollutants                  | Sources                                                                 | Health Effects                                                   |
|----------------------------------------|-------------------------------------------------------------------------|------------------------------------------------------------------|
| Respirable suspended particulates (PM$_{10}$) | *tobacco smoke;*  
*emissions from cooking and heating appliances;*  
*burning incense.* | *respiratory irritation and infection;*  
*aggravation of existing respiratory or cardiovascular disease;*  
*nasal and eye irritations.* |
| Volatile organic compounds (VOCs)      | *cleaning agents, cosmetics, waxes, carpets and paints;*  
*building and furnishing materials;*  
*office equipments like laser printers and photocopiers.* | *irritation;*  
*nervotoxic effects;*  
*hepatotoxic;*  
*carcinogenic.* |
| Biological contaminants (Viruses, bacteria, fungi, molds, insects) | *outdoors;*  
*humans;*  
*animals.* | *allergic reactions;*  
*infectious diseases;*  
*irritations;*  
*local effects.* |
| Environmental tobacco smoke (ETS)      | *tobacco smoke* | *irritation to mucous membranes;*  
*chronic and acute pulmonary effects;*  
*cardiovascular effects;*  
*carcinogenic.* |
| Formaldehyde (also a VOC)               | *ETS;*  
*building materials and fabrics;*  
*cleaning fluids and adhesives.* | *irritation to eye, nose and respiratory system;*  
*allergy;*  
*carcinogenic.* |
| Asbestos                               | *asbestos cement;*  
*building materials like pipe lagging, ceiling tiles.* | *carcinogenic;*  
*asbestosis (scarring of lung tissues).* |
| Radon and its decay products           | * soils and rocks especially granite in HC;*  
*building materials.* | *carcinogenic.* |
| Carbon monoxide                        | *combustion appliances;*  
*cooking;*  
*ETS.* | *headaches, flu-like symptoms, nausea, fatigue, chest tightness;*  
*cardiovascular diseases;*  
*death in high concentration.* |
| Nitrogen oxides                        | *combustion appliances;*  
*cooking;*  
*ETS.* | *irritation of respiratory system and eyes;*  
*decreased in pulmonary function in asthmatics;*  
*decreased immune capacity, changes in anatomy and function of lung.* |
| Ozone                                  | *photocopiers;*  
* laser printers.* | *irritation of eyes and respiratory tract;*  
*damage lung tissue.* |
| Sulphur dioxide                        | *combustion of fuels containing sulphur* | *decreased lung function in asthmatics.* |
Table 12.6-2. Sources, odor threshold and health impact of common indoor VOCs.

| Indoor VOCs | Sources | Color Threshold (ppm) | ACGIH Classification |
|-------------|---------|-----------------------|----------------------|
| Formaldehyde | Geranium, pressed-wood products, urea-formaldehyde foam insulation, UF, adhesives, paints, plastics, carpeting, gypsum board, ceiling tiles, and paneling, wood paneling | 0.03 | 2A |
| Benzene | ETS, solvents, paints, stove, cars, machines, computer terminals, printers, water-based adhesives, carpet, plastics, synthetic fibres | 12 | 1 |
| Carbon Tetrachloride | Solvents, refrigerant, aerosols, fuel, refrigerants, greases, solvents | 98 | 2B |
| Trichloroethylene | Solvents, dry cleaning fluids, paint thinners, paints, varnishes, adhesives, machines, computer terminals and printers, correction pen fluids, paint removers, spot removers | 28 | 2A |
| Tetrachloroethylene | Dry cleaning fluids, spot removers, cleaners, fuel, machines, computer terminals and printers | 27 | 2A |
| Chloroform | Solvents, food, pesticides, machines, computer terminals and printers, upholstery, chlorine water | 85 | 2B |
| 1,2-Dichloroethane | Dry cleaning agent, degreasing, insecticides, carpets | 0.3 | Inadequate data |
| 1,3-Dichloroethane | Insecticide | 0.3 | Inadequate data |
| 1,4-Dichlorobenzene | Deodorant, mild solvent, all-purpose detergents, fuel, tire cord, rubber, greases, solvents | 0.10 | Inadequate data |
| Ethylene | Stereographing process, adhesives, solvents, fuel, machines, computer terminals and printers, furniture polish, lacquer, and nontoxic collating compounds, floor tile adhesives, carpet fibers | 2.3 | Not classified |
| Toluene | Solvent, perfumes, detergents, dye, water-based adhesives, modelling clay, wax, cement, silicate, paint, carpeting, carpet adhesives, greases, solvents | 2.9 | 3 |
| Xylenes | Solvent, dye, inorganics, polyurethane, adhesives, wax, paper, varnish, carpeting, wet process paper, paint, preservatives, rubber, nails, floor tile adhesives, greases, solvents, paint, carpet adhesives | 2.9 | 3 |

1. ACGIH, Odor Thresholds for Chemicals with Established Occupational Health Standards (1993).
2. American Conference of Governmental Industrial Hygienists (ACGIH) Classifications:
   - Group 1: the agent is carcinogenic to humans (sufficient evidence of carcinogenicity in humans).
   - Group 2A: the agent is probably carcinogenic to humans (limited evidence of carcinogenicity in humans and sufficient evidence in experimental animals).
   - Group 2B: the agent is possibly carcinogenic to humans (inadequate evidence of carcinogenicity in humans but sufficient evidence in animals).
   - Group 3: the agent cannot be classified as to its carcinogenicity to humans.

Table 12.6-3. Summary of indoor air quality standards and guidelines for different countries.

| ITEM | Australia(1) | Canada(2) | China(3) | Hong Kong(4) | Japan | South Korea | Singapore | UK(5) | USA(6) |
|------|--------------|-----------|----------|--------------|-------|-------------|----------|-------|--------|
| Carbon monoxide | 9 ppm | 9 ppm | -- | 80 ppm | 10 ppm | 10 ppm | 10 ppm | 10 ppm | 10 ppm |
| Carbon dioxide | 1,000 ppm | 1,000 ppm | -- | 1,000 ppm | 1,000 ppm | 1,000 ppm | 1,000 ppm | 1,000 ppm | 2,000 ppm |
| SO2 | -- | 150 ppm | -- | 160 ppm | 0.15 ppm | -- | -- | -- | 150 ppm |
| TSP | 10 ppm | 10 ppm | -- | -- | -- | -- | -- | 0.15 ppm | -- |
| Radon | 200 Bq/m³ | 200 Bq/m³ | 200 Bq/m³ | -- | -- | -- | -- | 200 Bq/m³ | -- |
| Formaldehyde | 0.1 ppm | 0.1 ppm | 0.08 ppm | 0.1 ppm | -- | 0.01 ppm | -- | -- | -- |
| Nitrogen oxide | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Nitrogen dioxide | -- | -- | -- | 160 ppm | -- | -- | 3 ppm | -- | -- |
| Ozone | 0.1 ppm | 0.1 ppm | 0.08 ppm | 160 ppm | -- | -- | 0.05 ppm | 0.1 ppm | -- |
| VOC | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| TVOC | 500 ppm | 500 ppm | 500 ppm | 500 ppm | -- | -- | -- | 500 ppm | -- |
| Temperature | -- | -- | -- | 18-26°C | 17-29°C | 17-26°C | 22.5-25.5°C | -- | -- |
| Relative humidity | -- | -- | -- | 25-60% | 30-60% | 40-60% | 70% | -- | 65% |
| Air velocity | 0.15-0.25 m/s | 0.25 m/s | 0.25 m/s | 0.5 m/s | 0.5 m/s | 0.25 m/s | -- | -- | -- |
| Illumination | -- | -- | -- | -- | -- | -- | 100 Lux | -- | -- |

(1) Australian National Indoor Air Quality Guidelines recommended by NRMMC.
(2) Main reference is ASHRAE, AIA and ACOH guidelines, and ASHRAE in Office Buildings - A Technical Guideline 1995.
(3) ACGIH guidelines for indoor air guidelines.
(4) Standard Odour Concentration recommended by the researchers in this IAQ study.
(5) Occupational Exposure Limit for long term exposure (8 h TWA period).
(6) ACGIH indoor exposure guidelines (24 h TWA average).
12.6.1 Indoor Air Survey

Indoor air survey was carried out for Hong Kong domestic homes, as there are no available data in this category at the time. A clear understanding of the local indoor air pollution problem is invaluable for the success of the product.

12.6.1.1 Site selection criteria

The measurement sites are private residential homes selected on the basis of (1) the prevalence of housing types, (2) proximity to residential centers and (3) accessibility. Homes that had been renovated within the last five years have higher VOC level and were not considered in this survey. Six sites were selected based on the above criteria, but only four were surveyed (Table 14) because of the unfortunate outbreak of SARS during this period. An exact record of the sites was assembled starting with the building location, age and state of repair along with the district information, proximity of neighboring buildings and local traffic conditions that affects the ambient air quality. The residents provided the floor plan, apartment conditions and furnishings, ventilation and schedule of indoor activities (Table 12.6-4).

| Site | District     | District Condition                      | Type  | Age  | Floor | No. of Occupant | Pets | Cleaning Freq | Stove | Fuel  |
|------|--------------|-----------------------------------------|-------|------|-------|-----------------|------|---------------|-------|-------|
| 1    | Sai Kung     | Residential, moderate population with low traffic flow | Villa | 19 years | 1/F | 1 | 0 | 1/wk | Gas | LPG |
| 2    | Tsing Kwan 0 | Residential, high population with medium traffic flow | Private | 17 years | 22/F | 4 | 0 | >52/wk | Gas | Towngas |
| 3    | Kowloon Bay  | Commercial and residential mix with a nearby construction | Private | 18 years | 28/F | 4 | Fish | 2-3/wk | Gas | LPG |
| 4    | Clear Water Bay | Residential with low traffic flow | Private | 6 years | 7/F | 4 | 0 | 1/wk | Gas | Towngas |

12.6.1.2 Site modeling

Site modeling was carried out using the commercial software, FEMLAB to investigate the airflow and pollutant dispersion in each household. Site 2 is an apartment located in the 22nd floor of a 17 years old residential block shown in Fig. 12.6-1. The floor plan and photos of the apartment are included in Fig. 12.6-2. The irregular-shaped floor plan is the norm rather exception in Hong Kong, where space is a premium. The floor plan was drawn using AutoCAD and exported to FEMLAB. The airflow patterns and pollutant dispersion shown in Fig. 12.6-3 were obtained by solving the general material and momentum balance equations and Fick’s second Law [18]. The results show that the irregular apartment layout contributes to the complex flow pattern in the apartment. Stagnant air appears throughout the apartment where pollutants can accumulate. The modeling results were confirmed by experiment. Air pollution data at different locations in the apartment were obtained under different...
ventilation conditions and the results were in good agreement with the pollution profile predicted by the model. The model was therefore used to guide the air survey study.

Figure 12.6-1. (a) Map of the location and (b) photo of the residential block for site 2.

Figure 12.6-2. (a) Floor plan and (b) photo of the site 2 apartment.
Six common indoor air pollutants were selected based on their health impact, prevalence in Hong Kong and the availability of the right measurement equipments. They are the carbon monoxide (CO), formaldehyde (HCHO), total volatile organic carbons (TVOCS), aerosols (PM2.5/PM10), bioaerosols and carbon dioxide (CO₂). The carbon dioxide measurement was included as an indicator for the adequacy of ventilation. Measurements were conducted over a period of five days at each selected sites with the permission of residents. One day is needed to set up and calibrate the equipments. Real time monitoring of the temperature, humidity, aerosol, carbon monoxide, carbon dioxide and formaldehyde were conducted at each sites for the next 72 hours using equipments listed in Table 12.4-3. The air samplings for formaldehyde, TVOC
and bioaerosols were done when the residents were away from home to avoid inconvenience. The formaldehyde and total VOCs were sampled using sorbent tubes and analyzed in the Applied Technology Center (ATC) laboratory using gas chromatography. Airborne bacteria and fungal spores were sampled using Andersen-type bioaerosol impactor using tryptic soy agar (TSA) and malt extract agar (MEA) plates, respectively. The viable colonies were counted after sample incubation. The residents were interviewed on the last day before the equipments were disassembled and removed.

Table 12.6-5 summarizes the results of the indoor air quality survey conducted at each sites and compared to air quality standards recommended by the Hong Kong Environmental Protection Department for very good indoor air quality (Level 1). All four sites have relatively good ventilation and their eight hours average carbon dioxide levels were high but remain within the recommended value. The 8-hours average level of respirable suspended particles (RSP) at all four survey sites exceeded the HKEPD’s level 1 recommendation. The high level of PM2.5 is a cause for alarm, as it is suspected to contribute to lung cancer. The sources of RSP are from nearby construction site and local traffic. Most originated from human activities such as cooking as the surges in the RSP level coincided with meal times. The airborne bacteria level is also high at all the sites, and despite conducting the sampling when residents were at work, site 3 & 4 exceeded HKEPD level 1 & 2 recommendations. This is found to correlate to the number of residents and their cleaning habits (Table 12.6-4). The carbon monoxide level is low for apartments with separate kitchen area, but at site 4 where the kitchen is attached to the living room, the carbon monoxide level is high and exceeds the recommended level when the residents were cooking. The formaldehyde, benzene, toluene and xylene levels are low as no recent renovations were done and all residents were nonsmokers. The survey results were in good agreement with a more detailed air quality survey of twenty Hong Kong apartment homes (Table 12.6-6) commissioned by the team with funding from the Hong Kong Innovation and Technology Commission.

The results of the air quality surveys and interviews with the residents indicated that dust, particulates and bioaerosols are major problems in Hong Kong residential homes. The high level of carbon monoxide produced during cooking must be addressed. Odors are the most common complaints from the residents despite the recorded low level of VOCs. This is understandable since the threshold odor for most of these compounds is very low. The team therefore recommends that the product should feature aerosols (i.e., dust and particulates), bioaerosols (i.e., airborne bacteria and fungi), carbon monoxide and odor (i.e., VOCs) removal technologies.
Table 12.6-5. Indoor air pollution at the four selected sites.

| Pollutant | Site 1 (ppm) | Site 2 (ppm) | Site 3 (ppm) | Site 4 (ppm) | HKEPD level 1 |
|-----------|--------------|--------------|--------------|--------------|---------------|
| CO₂       | 480          | 500          | 360          | 400          | < 800         |
| RSP (μg/m³) |             |              |              |              |               |
| PM₁₀      | 80           | 110          | 115          | 120          | < 20          |
| PM₂.₅     | 65           | 110          | 100          | 115          | not available |
| CO (ppb)  | 30           | 50           | 100          | 1800         | < 2000        |
| HC₅O (μg/m³) | < 10        | < 10         | -            | < 10         | < 100         |
| Benzene (μg/m³) | 1           | 1.4          | 1.3          | 0.7          | < 16.1        |
| Toluene (μg/m³) | 0.9         | 4.8          | 4.6          | 3.8          | < 1092        |
| Xylene (μg/m³) | 0.2         | 0.8          | 0.5          | 1.8          | < 1447        |
| Bacteria (CFU/m³) | 480          | 440          | 1080         | 700          | < 600         |

Table 12.6-6. Hong Kong indoor air quality survey.

| Pollutants               | Units | HKEPD MAC O₂ (8 h) | Domestic Households (summer)¹ | Domestic Households (winter)² | Offices³ | Restaurant⁴ | Cinema⁵ | Shopping Mall⁶ |
|--------------------------|-------|--------------------|-------------------------------|-------------------------------|----------|-------------|---------|---------------|
| CO                       | μg/m³ | 10,080             | --                            | --                            | 0.8      | 3.3         | 1.7     | 1.7           |
| CO₂                      | ppm   | 1,000              | 461                           | 567                           | 980      | 1271        | 1382    | 1002          |
| HCHO                     | μg/m³ | 100                | 77                            | 14                             | 71       | 162         | 140     | 39            |
| RSP                      | μg/m³ | 180                | 87                            | 76                             | 30       | 323         | 55      | 78            |
| Benzene                  | μg/m³ | 16.1               | 0.3                           | 4.0                            | 6.6      | 12.2        | 1.88    | 5.0           |
| m-Dichlorobenzene        | μg/m³ | 600                | 21.9                          | 5.0                            | 2.0      | 0.9         | 1.8     | 1.5           |
| Ethylbenzene             | μg/m³ | 14.47              | 1.8                           | 8.5                            | 20.4     | 7.7         | 3.8     | 8.3           |
| Tetrachloroethene        | μg/m³ | 250                | 5.4                           | 9.0                            | 3.0      | 5.6         | 1.6     | 1.9           |
| Toluene                  | μg/m³ | 1092               | 19.7                          | 17.4                           | 250      | 104         | 7.6     | 86            |
| Trichloroethylene        | μg/m³ | 770                | not measured                  | not measured                   | 28.2     | 1.92        | 0.5     | 2.7           |
| o-Xylene                 | μg/m³ | 1447               | 3.7                           | 8.3                            | 15.0     | 0.6         | 0.8     | 7.6           |
| m, p-Xylene              | μg/m³ | 1447               | 2.7                           | 4.2                            | 25.9     | 22.9        | 17.9    | 19.0          |
| bacteria                 | CFU/m³| 1000               | 134                           | 796                            | 740      | 1002        | 430     | 2146          |
| fungi                    | CFU/m³| 500                | not measured                  | not measured                   | 187      | 77          | 26      | 330           |

¹Indoor air pollution survey carried out with funding from HKITC and contracted to Aeon International Technologies, Inc.
²Data based on surveys conducted by EHS Consulting Ltd Agreement # CE 14955

12.7 CATALYST AND ADSORBENT

Filtration is an efficient and inexpensive method for removing dust, particulates and bioaerosols from indoor air. High efficiency filters can remove up to 95% of airborne particles as small as 0.3 microns. However, odor associated with gaseous VOCs cannot be removed by simple filtration and must be captured using adsorbents such as activated carbon and charcoal. Frequent replacement is needed since these adsorbents have finite capacity and cannot be regenerated. The aim of this project is to develop an effective remediation technology for common airborne VOCs found indoor.

12.7.1 Catalyst Formulation

An efficient, low temperature oxidation catalyst was developed based on highly disperse metal catalyst on nanostructured TiO$_2$ support. The nanostructured catalyst proved to be resistant to most common poisons found in the environment including halogen- and sulfur-containing compounds. The addition of vanadium oxide dopant promotes the catalytic activity, inhibits metal sintering and prevents deactivation [18]. A simple factorial design was used to guide the catalyst research. Table 12.7-1 lists the experimental variables and their value range.

Table 12.7-1. Experimental variables for catalyst research

| Experimental Variables          | (-)       | (+)       |
|--------------------------------|-----------|-----------|
| TiO$_2$ support (11 nm)         | hydrothermal | thermal   |
| Vanadium oxide                 | monomeric | polymeric |
| Metal                          | Metal 1   | Metal 2   |
| Metal loading (wt.%)           | 0.1       | 1         |

12.7.2 Catalyst preparation and characterization

The 11 nm-sized TiO$_2$ were crystallized using either hydrothermal or thermal methods from 100 nm, amorphous gel spheres. The TiO$_2$ crystal and agglomerate sizes were determined by X-ray diffraction (Philip 1080) and transmission electron microscopy (JEOL JEM 2010), respectively. The surface area and chemistry of the nanostructured TiO$_2$ were analyzed by nitrogen physisorption (Coulter SA 3100) and Fourier transform infrared spectroscopy (FTIR, Perkin-Elmer GX 2000). Metal catalyst was deposited by incipient
wetness method from salt precursor. A low and high metal catalyst loading of 0.1 and 1 weight percents were prepared. Low temperature ozone pretreatment was used to decompose the salt precursor and obtain well-dispersed metal catalysts. Monomeric or polymeric vanadium oxide was then deposited. The overall composition of the prepared catalyst was determined by inductively coupled plasma, atomic emission spectrometer (ICP-AES, Perkin Elmer Optima 3000XL) after acid digestion, while its surface composition was analyzed by X-ray photoelectron spectroscopy (XPS, Physical Electronics PHI 5000). The metal catalyst and dopant dispersions were established by carbon monoxide chemisorption (Altamira Instruments AMI-200) and micro-Raman spectroscopy (Renishaw Raman microscope 160).

12.7.2.1 Catalyst optimization
Catalysts were tested for oxidations of carbon monoxide and toluene. The tests were carried out in a differential reactor shown in Fig. 12.7-1 and analyzed by an online gas chromatograph (HP 6890) equipped with thermal conductivity and flame ionization detectors. Gases including dry air and carbon monoxide were feed to the reactor by mass flow controllers, while the liquid reactant, toluene was delivered by a syringe pump. Thermocouple was used to monitor the catalyst temperature. Catalyst screening and optimization identified the best catalyst formulation with a conversion rate for carbon monoxide and toluene at room temperature of 1 and 0.25 mmole$^1$g$^{-1}$min$^{-1}$. Carbon monoxide and water were the only products of the reactions.

Figure 12.7-1. Schematic diagram of the reactor set-up for catalyst performance test.
12.7.3 Adsorbent Formulations

12.7.3.1 VOCs adsorbent
A regenerable adsorbent for VOCs capture was prepared by chemical and structural modifications of mesoporous silica, MCM-41. The adsorbent has a large adsorption capacity for VOCs, fast adsorption rate, excellent regenerability (i.e., low regeneration temperature and fast regeneration) and superior hydrothermal stability. The MCM-41 powder was prepared from an alkaline synthesis solution containing tetraethyl orthosilicate (TEOS, 98%), cetyltrimethylammonium bromide (CTABr, 99.3%) and ammonium hydroxide (NH₄OH, 28-30 wt.%) at a molar ratios of 6.58 TEOS: 1 CTABr: 292 NH₄OH: 2773 H₂O. The synthesis was conducted at room temperature under vigorous mixing to obtain well-dispersed, micron-sized particles. The MCM-41 was filtered, washed, dried and ground to obtain free flowing powder. The powder was collected and calcined in a single batch at 823 K for 24 h to burn away the organic templates. The MCM-41 was subjected to chemical and structural modifications. The particle size of MCM-41 was determined by scanning electron microscopy (SEM, JEOL JSM 6300F). A detailed description of the particle morphology and pore structure was obtained using a high resolution, transmission electron microscope (TEM, JEOL JEM 2010), while the average surface area and pore size were calculated from nitrogen physisorption experiments (Coulter SA 3100) and X-ray diffraction data (XRD, Philip 1080).

The modified MCM-41 adsorbents were coated on a monolith and tested in a flow cell shown in Fig. 12.7-2. A pressure regulator and a flowmeter were used to adjust the airflow to a saturator containing the target volatile organic compound. A separate air stream was used to dilute and control the concentration of the feed VOCs. VOC sensors located at the flow cell inlet and outlet were used to monitor airborne VOC concentrations. Figure 12.7-3 depicts the results of a typical experimental run involving VOC adsorption at ambient temperature and regeneration at 423 K. The adsorption capacity, adsorption rate and regeneration rate were determined. The best adsorbent has adsorption capacities for ethanol, acetone and oil of 0.4, 0.8 and 10g per gram of adsorbent. The adsorption and regeneration are rapid and are often completed within 5 minutes.
12.7.3.2 Desiccant

A new desiccant formulation was prepared from a mixture of submicron-sized silica gel and molecular sieves to achieve the best combination of large water capacity, rapid moisture adsorption and easy regenerability. The formulation also tolerates the presence of VOCs and smokes. Commercial NaX and silica gel were crushed and mixed in the proportion of 1:2 and wash coated on a monolith for testing. The same test cell shown in Fig. 12.7-2 was used. The airflow to the saturator was adjusted to obtain the desired humidity in the feed air. Humidity sensors located at the flow cell inlet and outlet, were used to
monitor the moisture content of the air. The adsorption capacity of the desiccant mixture was about 0.7 g/g with an adsorption rate of 1.2 g g⁻¹min⁻¹ and a regeneration rate of 0.7 g g⁻¹min⁻¹ at 423 K.

12.7.4 Catalyst-adsorbent monolith wheel

A powder formulation containing the appropriate amounts of catalyst, adsorbent and desiccant will be formed into a monolith. Monoliths are characterized by low-pressure drop and large geometric surface area. The open channel structure makes monolith less susceptible to fouling. Ceramic monoliths with cell densities of 25 to 1600 cells per square inch (i.e., cell sizes of 5 - 0.6 mm) are routinely made by extrusions. The process involves powder blending, pugging, extrusion, cutting, drying and sintering to produce the final monolith. Powder preparation is considered to be the most critical step in monolith forming. The catalyst being sensitive to many of the chemical additives and processing steps used in the extrusion process would be separated coated onto the prepared monolith. The adsorbent and desiccants are of different sizes and proper mixing, grinding and screening are needed to produce a free-flowing powder of narrow particle size distribution. Particle sizes larger than 5 microns are not suitable for extrusion. Computer software loaned by Prof. K.M. Ng groups provided a guide for powder processing. The recommended process for obtaining 2 microns powder is shown in Fig. 12.7-4. Suitable binder, surfactant, deflocculant, coagulant, lubricant, plasticizer, and preservative are needed to prepare an extrudable mixture. Unfortunately, the high cost of extrusion die prevented the team from producing their own monolith, instead commercial desiccant monoliths were purchased and coated with the low-temperature catalyst and regenerable VOC adsorbent.
12.8 PROTOTYPE DESIGN

A. Rational Design Approach
Cross [19] advocates a rational approach in the design process. He described in his book the seven steps procedure for the “rational method for new design” shown in Fig. 12.8-1 and listed in Table 12.8-1. The method covers every aspects of the design process from problem clarification to detailed design. It also facilitates better teamwork and enables better task subdivision. The project team employed this method to guide the design of the indoor air quality control appliance.

![Figure 12.8-1. Schematic of the rational method for new design [20].](image)

12.8.1 Clarifying Objectives
The project team’s main objective is to design an efficient indoor air quality control appliance that can achieve the most stringent IAQ standard using new and competitive catalyst and adsorbent technologies. The appliance must be
safe, reliable, user-friendly and cost-competitive. This is summarized in the objective tree shown in Fig. 12.8-2.

Table 12.8-1. Rational method for new design [20]

| Stage | Design Stage               | Design Objective                                                                 |
|-------|----------------------------|----------------------------------------------------------------------------------|
| 1     | Objective Tree             | clarify design objectives and sub-objectives, and their relationships             |
| 2     | Function Analysis          | establish the required function and system boundary of the new design             |
| 3     | Performance Specification  | create an accurate performance specification required by the design solution      |
| 4     | Quality Function Deployment| set targets for the engineering characteristics of the product that satisfy the customers’ requirements |
| 5     | Morphological Chart        | generate a complete range of alternative design solutions in order to broaden the search for potential new solutions |
| 6     | Weighted Objectives        | assess the added value of each design proposal based on different weighted objectives |
| 7     | Value Engineering          | increase or maintain the value of the product to its customer, while reducing its production cost |

Figure 12.8-2. Objective tree for indoor air quality control appliance.

12.8.2 Establishing Functions

The indoor air quality appliance must have better than ninety percent efficient in removing airborne particulates, bioaerosols (i.e., airborne bacteria and fungi spores), carbon monoxide, volatile organic compounds and odors. It must meet or exceed the industry’s standards in performance and safety. The product must be able to maintain the pollutants in indoor air at below government IAQ standards and must not emit or produce harmful secondary pollutions during
operation. The manufacturing cost should not exceed US$100 and preferably within US$50 per units.

12.8.3 Setting Requirements

Next, the team identified the performance, safety, customer, marketing and manufacturing requirements for the indoor air quality control appliance.

12.8.3.1 Performance requirements
1. removes better than 95 percent of airborne particles and microorganisms with sizes down to 0.3 micron,
2. converts carbon monoxide up to 5000 ppm, into harmless carbon dioxide,
3. removes better than 90 percent of volatile organic compounds (VOCs) up to 30 ppm and better than 50 percent of VOCs up to 200 ppm,
4. converts VOCs into harmless carbon dioxide and water,
5. kills and inactivates better than 50 percent of airborne bacteria and fungi spores,
6. converts inactivated bacteria and fungi spores into harmless carbon dioxide and water,
7. deodorizes air of tobacco and incense smokes, cooking odors and others,
8. dehumidifies the air at a rate not less than 10 L/day at 20°C and 80 percent relative humidity,
9. cleans and dehumidifies a room size not smaller than 20 m²,
10. maintains a clean air delivery rate (CADR) not less than 50 cfm,
11. power consumption not to exceed 200 W,
12. design life of at least 10,000 h (i.e., 4.5 years),
13. light and portable with weight not exceeding 10 Kg.

12.8.3.2 Safety requirements
1. complies with industry safety standards,
2. must not contain any hazardous materials and all materials must be clearly identified,
3. includes redundant safety features and intelligent control devices to ensure safe and optimal performance,
4. simple user friendly operation with clearly labeled instructions.

12.8.3.3 Customer requirements
1. cleans, disinfects and deodorizes indoor air,
2. delivers clean and comfortable air on demand or automatically,
3. low cost,
4. simple user friendly operation with smart automatic functions,
5. minimal upkeep and maintenance,
6. built-in air quality monitoring and display
7. smart and attractive appearance,
8. portable and compact design,
9. silent operation,
10. energy efficient and environmentally-friendly manufacturing and materials.

12.8.3.4 Marketing requirements
1. high efficiency air cleaner for particulate, allergen, pathogen, odor and VOC removal and remediation,
2. product certification, independent laboratory tests and customer’s testimonial,
3. new proprietary or breakthrough technology that differentiate the product from the competitors,
4. potential to generate a new series of product lines,
5. extra functional features and add-ons,
6. user-friendly and smart features
7. attractive and compact design,
8. competitive pricing.

12.8.3.5 Manufacturing requirements
1. minimize the number of major component parts,
2. lower production cost by subcontracting the design and manufacture of major component parts (e.g., heater, blower, fan, control panels, power supply, etc.),
3. keep the assembly process simple with no more than 15 steps,
4. manufacture the core technology in-house to keep better quality assurance,
5. employ environmental friendly manufacturing approach using recycled materials and easily recyclable component parts,
6. maintain a clean and safe working environment,
7. build a production line with capacity of at least 1000 units per months.

12.8.4 Determining characteristics

The indoor air quality control appliance consists of air handling, filtration, purification and dehumidification systems. Mr. Peter Chan of Chiaphua Industries Ltd. was closely consulted in completing the engineering specifications for the product.

12.8.4.1 Air handling system
An air inlet area of at least 400 cm² and a louvered exit of 75 cm² are recommended for target capacity and physical size of the appliance. The efficient and quiet centrifugal fan unit is popularly used in air conditioners and air purifiers. It costs less than the other fan units of similar size and is easy to install and assemble. A fan with adjustable air deliver rate of 0 to 250 cfm will be used to draw air through the air filter, dehumidifier and purifier units. A smaller fan with air delivery rate of up to 10 cfm is needed for the regeneration
air stream. The air is heated by electric heating coil (100 W) that is safe and easy to control. A simple thermostat and control circuit to prevent overheating and cuts heater power when fan is accidentally turned-off. A simple programmable logic circuit for the heater system can reduce the energy consumption by more than sixty percent and incorporate safety programming to minimize temperature spikes during shut-down. The hot air will be channeled and mixed will cool air before discharge.

12.8.4.2 Air filtration system
Airborne particles, bacteria, fungi spores and allergens will be removed by air filtration, which is often cheaper and more effective than electrostatic precipitators and ionizers. A disposable, high-efficiency filter capable of removing at least 95 percent of particles with size down to 0.3 micron will be installed. A washable coarse filter that removes fifty percent of particles larger than 10 microns will be used as a pre-filter to extend the life of the high efficiency filter by at least a third. An inexpensive sensor will be included to indicate when filter replacement is necessary.

12.8.4.3 Air purification system
Today, adsorption by activated carbon, charcoal and permanganate-coated alumina is the most common method for odor and VOCs removal. However, the adsorbent can become quickly saturated and may require frequent replacement. UV-activated photocatalytic oxidation (PCO) is popular in Japanese air purifier and is proven to be effective in odor removal. However, PCO reaction is slow and byproducts are often formed. This project introduces the use of regenerable adsorbent based on modified mesoporous silica and an efficient low temperature VOCs oxidation catalyst for VOCs removal and conversion into harmless carbon dioxide and water. The catalysts and adsorbents are coated on a honeycomb wheel that rotates at less than 20 revolutions per hour (rph). Seventy percent of the honeycomb area is exposed to incoming air at any given time, while the remaining area is undergoing high temperature (i.e., up to 100ºC) regeneration. Calculation indicates that at least 8 g of adsorbents and 0.5 g of catalysts are needed to maintain a better than 90 percent removal of VOCs up to 30 ppm concentration.

12.8.4.4 Air dehumidification system
There are several desiccant-based, sorption dehumidifier designs in the market. Two commercial designs are illustrated in Fig. 18. The basic sorption dehumidifier shown in Fig. 12.8-3a has the advantage of simplicity in design, but air temperature leaving the unit can be as high as 40ºC. A compressor-assisted unit (Fig. 12.8-3b) has higher capacity and lower temperature but is more complex and expensive. Desiccant wheels made of silica gel, zeolites and activated alumina can be purchased in a wide-range of shapes and sizes. A NaX zeolite honeycomb wheel of 217 mm diameter and 21 mm thickness is
necessary to remove 10 L of water per day when the room conditions are 20°C and 80 percent relative humidity. A quiet, high torque universal motor will be used to rotate the wheel at variable speed of up to 20 rph. At any one time, seventy percent of the wheel will be adsorbing moisture, while the remaining thirty percent is being regenerated. The hot airstream used in regeneration is channeled to an air-cooled condenser where the water is condensed and collected in a tank for later disposal. A simple water level indicator will be installed to give warning and stop the unit when the tank is full.

![Figure 12-8.3](image)

Figure 12-8.3. Schematic drawing of (a) basic sorption dehumidification process and (b) compressor-assisted air dehumidification process.

### 12.8.4.5 Other specifications

The size of the unit must not be bigger than 0.25 m \((w)\) x 0.25 \((d)\) x 0.35 m \((h)\), which are the dimensions of common air purifiers of similar capacity. The appliance must weigh less than 10 Kg and should have lockable caster wheels for ease of transport around the house. An ergonomic and user-friendly read-out and control units will be provided to indicate the room’s air quality and appliance operation.

### 12.8.5 Generating alternatives

Brainstorming sessions were conducted during the course of the product design. Each team was encouraged to pre-work the design problem along the stated objectives and requirements before the sessions. The sessions included all the team members and were guided by a guest moderator from industry. After each session, the ideas were grouped, categorized and discussed. The best design features were kept and refined before incorporating into the overall design. From these sessions, the prototype design team was able to propose ten viable, alternative appliance designs of which three will be discussed in detail.
12.8.5.1 Product design 1

The design employs filters for particulate removal, a desiccant wheel for air dehumidification and a catalyst-adsorbent wheel for air purification. Dehumidification discourages microbial growth in particular mildews and fungi. It also safeguards the performance of the catalyst-adsorbent wheel by removing moistures that may interfere with the catalyst and adsorbent. The use of two wheels design solves material compatibility problems and allowed independent performance optimization. However, the design is complicated and expensive.

Figure 12.8-4 displays a schematic flow diagram of the product design 1. The air is drawn-in through a washable, coarse filter (1) that removes particles larger than 10 microns and a disposable high efficiency filter (2) that removes 95 percent of particles with size down to 0.3 microns. The filtered air flows through a desiccant wheel (3) decreasing the relative humidity of the air to below 50 percent. A second set of wheel (4) coated the low temperature VOCs oxidation catalyst based on nanostructured catalyst converts organic pollutants into harmless carbon dioxide and water at ambient temperature. The wheel was also coated with regenerable VOCs adsorbent made from modified mesoporous silica to capture excess VOCs. The clean, dry air leaving the catalyst-adsorbent wheel flows past the air-cooled condenser before leaving the unit.

Figure 12.8-4. Schematic flow diagram for the product design 1.
A second stream of air with flow rate one-twentieth of the main airstream was heated and used to regenerate the catalyst-adsorbent and desiccant wheels. The heated air desorbs the organic pollutants captured in the adsorbent. The elevated temperature increases the catalyst activity enabling complete oxidation of the desorbed VOCs. The heated air then enters the desiccant wheel desorbing the adsorbed water and regenerating the desiccant. The hot, moist air is guided into an air-cooled condenser where water is condensed and collected in a reservoir pan. The two air streams are mixed and guided through a baffle before exiting the unit.

12.8.5.2 Product design 2
The design employs filters for particulate removal, a desiccant-VOCs adsorbent wheel for simultaneous air dehumidification and purification. The catalyst was coated on a separate sleeve directly across the hot air stream. This design eliminates the need for separate wheels and is both cheaper and simpler to manufacture. The higher temperature and pollutant concentration in the regeneration stream mean higher catalyst activity. However, the small flow rate and high moisture content of the regeneration stream can result in a poorer overall performance.

Figure 12.8-5 displays a schematic flow diagram of the product design 2. The air is drawn-in through a washable, coarse filter (1) that removes particles larger than 10 microns and a disposable high efficiency filter (2) that removes 95 percent of particles with size down to 0.3 microns. The filtered air flows through a desiccant-VOCs adsorbent wheel (3) decreasing the relative humidity of the air to below 50 percent and the airborne VOCs content to below IAQ standard. The clean, dry air leaving the desiccant-VOCs adsorbent wheel flows past the air-cooled condenser before leaving the unit. A second stream of air with flow rate one-twentieth of the main airstream was heated and used to regeneration the desiccant-VOCs adsorbent wheel. The heated air desorbs the water and organic pollutants adsorbed in the desiccant and adsorbent. The hot, moist air containing desorbed organic pollutants flows through a ceramic sleeve coated with the low temperature VOCs oxidation catalyst. The cleaned air is guided into an air-cooled condenser where water is condensed and collected in a reservoir pan. The two air streams are mixed and guided through a baffle before exiting the unit.

12.8.5.3 Product design 3
The design employs filters for particulate removal, a single desiccant wheel coated with both low temperature VOCs oxidation catalyst based on nanostructured catalyst and regenerable VOCs adsorbent made from modified mesoporous silica. The distribution of the active elements along the wheel thickness was optimized and shown in Fig. 12.8-6. The adsorbents are coated along two-thirds of the wheel thickness and all catalysts are concentrated on one
face of the wheel away from the entry point of the main airstream. This is a simpler design using less component parts and therefore cheaper to manufacture. It also allows easy conversion of existing commercial desiccant dehumidifier appliances into efficient air purifiers.

Figure 12.8-5. Schematic flow diagram for the product design 2.

Figure 12.8-6. Schematic drawing of the active element distributions along the wheel thickness.
Figure 12.8-7 displays a schematic flow diagram of the product design 3. The air is drawn-in through a washable, coarse filter (1) that removes particles larger than 10 microns and a disposable high efficiency filter (2) that removes 95 percent of particles with size down to 0.3 microns. The filtered air flows through a wheel containing desiccant, VOCs adsorbent and nanostructured catalyst. Water was removed first as the air flows past the desiccant, then the VOCs is removed by the adsorbent and catalyst. Concentrating the catalysts and adsorbents near the exit face of the wheel make certain that during regeneration all desorbed VOCs are effectively converted into harmless carbon dioxide and water. The hot clean air then desorbs the water and regenerates the desiccant before flowing through an air-cooled condenser where water is condensed and collected in a reservoir pan. The two air streams are mixed and exit the unit at near room temperature.

Figure 12.8-7. Schematic flow diagram for the product design 3.

12.8.6 Evaluating Alternatives

Only three of the stated objectives (Fig. 12.8-2) are relevant for this assessment phase. They are (1) air purification performance (50 %), reliability (25 %) and cost (25 %). In the absence of hard data, the members of the project team were
asked to rate each of the alternate designs relying on their own practical intuition. The industrial and faculty guests were also invited to participate in the process. The three highest ranked designs were discussed in the previous section. Despite the more complicated design and higher cost of the product design 1, it was believed to have better performance features than the other two designs.

12.8.7 Improving Details

The preliminary cost analysis was conducted with the help of Mr. Peter Chan of Chiaphua Industries Ltd. Table 12.8-2 compares the cost of subcontracting the manufacture of plastic and metal appliance components versus manufacturing in-house for a production volume of 1000 units per month. All calculated costs are below the US$ 100 limit. A cost saving of twenty percent was forecasted assuming that the facility will be built and operated in China where the land and labor costs are cheaper.

Once the detailed dimensions and possible arrangements of the components were known, the appliance size and dimension can be determined. The students conducted a detailed design of the appliance’s external casing using SolidWorks® 2001, a commercial mechanical design automation software, for detailed design of the appliance. The software makes it possible to quickly sketch ideas, experiment with features and dimensions and produce models and detailed drawings. The best arrangement places the air intakes along the sides of the appliance and the air exits at the top. A retractable water bucket with transparent window allow easy water disposal. Casters and retractable handles are included to improve mobility. These criteria were included in the final design and a 3D model was generated using the software and exported to a Rapid Prototyping Machine in HKUST’s department of Industrial Engineering and Engineering Management to produce a quarter-size model of the finished product. The details of this process are illustrated in Fig. 12.8-8.

Figure 12.8-8. Using computer-aided design software and rapid prototyper to create product from a design blueprint.
Table 12.8-2. Estimated production cost.

| Components                  | Subcontract/Assembly (US$) | Manufacture (US$) |
|-----------------------------|---------------------------|-------------------|
|                             | Design 1       | Design 3       | Design 1     | Design 3     |
| Plastic housing and parts   |                 |                 |              |              |
| Upper and bottom bodies     | 16.00          | 6.50\(^1\)    |              |              |
| Water tank                  |                |                 |              |              |
| Bottom wheel support        |                |                 |              |              |
| Motor support and assembly  |                |                 |              |              |
| Fan blades                  |                |                 |              |              |
| Fan covers                  |                |                 |              |              |
| Metal components            | 7.50           | 3.00\(^1\)    |              |              |
| Condenser                   |                |                 |              |              |
| Screw and others            |                |                 |              |              |
| Wheels                      | 17.00          | 11.00          | 11.00\(^1\) | 8.00\(^1\)  |
| Desiccant wheel             |                |                 |              |              |
| Catalyst-adsorbent wheel    |                |                 |              |              |
| Electrical and electronics  | 25.00          | 25.00\(^2\)   |              |              |
| Sensor and logic controller |                |                 |              |              |
| Displays                    |                |                 |              |              |
| Motors                      |                |                 |              |              |
| Heaters                     |                |                 |              |              |
| Power supply                |                |                 |              |              |
| Electrical cord             |                |                 |              |              |
| Packing                     | 2.50           | 2.50\(^2\)    |              |              |
| Gift box and master cartoon |                |                 |              |              |
| Foam blocks                  |                |                 |              |              |
| Instruction manual          |                |                 |              |              |
| Poly bag                    |                |                 |              |              |
| Labor and other costs       | 4.00           | 8.00           |              |              |
| Value Engineering           | 72.00          | 66.00          | 56.00        | 53.00        |

\(^1\)Equipment and operating costs were included with exception of labor cost.
\(^2\)It is more efficient to subcontract electrical and electronic components and packaging materi

B. Assembly and Test of Prototype Units
In order to produce a functional prototype unit within the remaining three month of the project, two commercial desiccant-based dehumidifier appliances (Zojirushi’s RV-D60-HC) were purchased from Japan in March 2003. The
appliances were disassembled and component parts were borrowed for the construction of the prototype indoor air quality control appliance.

12.8.8 Prototype Unit Design 1

Two honeycomb wheels were borrowed from the dehumidifier appliances for constructing the prototype design 1. The desiccant wheels contain NaX zeolite that adsorbs moisture but not VOCs. One of the wheels was coated with 12 grams of active formulation containing the modified mesoporous silica adsorbent and low temperature oxidation catalyst. The borrowed component parts were reassembled as shown in Fig. 12.8-9a. The wheel housing has to be modified and reconstructed to contain both wheels. A temporary external casing was used (Fig. 12.8-9b) before the final prototype was built. Airtight channels and seals for the hot air stream between the two rotating wheels were difficult to design and fabricate.

Sensors were inserted in the prototype to monitor the temperature (National Semiconductors, LM35-DZ), humidity (Honeywell, HIH-3605-B) and total VOC concentration (FIS, SP3-AQ2) at various locations shown in Fig. 12.8-10. The data were collected by a data logger (Picolog, ADC-16) and analyzed. The temperature profiles from the preliminary test showed that poor seal between the hot and cool air streams compromised the prototype performance. Hot spots and uncontrollable temperature rise prevented further tests. This clearly showed that the complicated design is not suitable.
Figure 12.8-10. Schematic drawing of the prototype unit design 1 showing the locations of the temperature, humidity and total VOC sensors.

12.8.9 Prototype Unit Design 3

The prototype design 2 was expected to have similar air seal problems as the prototype 1 therefore the prototype design 3 was constructed and tested, instead. Since all the modification was restricted to the wheel, prototype design 3 allowed us to simply use the existing commercial appliance design. The dehumidifier was first test run under different operating conditions and the airflow, temperature and humidity at different locations within the appliance were measured and recorded. The airflow, temperature and humidity profiles were used to calculate the optimum quantities and distributions of catalysts and adsorbents in the wheel (Fig. 12.8-6). The wheel was replaced in the dehumidifier appliance and tested with sensors inserted at the locations shown in Fig. 12.8-11. The results show that the airflows and temperatures remained within normal operating values. Laboratory and field tests were conducted and the results are reported in the next section.
12.9 LABORATORY AND FIELD TESTS

Phase two of the project commenced in May 2003 with the objectives of implementing the new catalyst formulation and prototype design and conducting detailed performance tests in the laboratory and field sites. The single catalyst/adsorbent/desiccant wheel has the advantage of simpler design and lower cost. The new prototype design was implemented towards the end of the spring semester and a new team of undergraduate students was recruited to continue the project. Ms. Hazel Lai Wing Yan, Ms. Vivian Chan Ngar Wai, Mr. Kenneth Leung Wai Kin and Mr. Owen Luk Ka Fai were all first year Chemical Engineering students. Mr. Anthony Ng Ka Hang, a graduate of Manufacturing and Industrial Engineering and former employee of Honeywell Consumer Products (HK) Ltd. joined to lead the team of undergraduates and take charge of prototype fabrication and testing. Hazel and Vivian were responsible for the laboratory tests, while Kenneth and Owen carried out the field tests. The FYP students remained for a month to help in the new prototype design and in
training the new team. Mr. Victor Lo of Global Manufacturing Services Ltd. and Mr. Eddy Wu of Chiaphua Industries Ltd. remained the project’s main industrial partners and consultants.

Eight desiccant-based dehumidifiers (RV-DA60-HC) made by the Japanese company Zojirushi (Fig. 12.9-1a) were purchased with the help of Chiaphua Industries Ltd. The appliance was designed for dehumidification of a 60 m² room at a rate of 3.36 L/day when the relative humidity (R.H.) is 50%. Its airflow can be adjusted between 65 and 85 m³/h (i.e., 40 to 50 scfm). The normal outlet air temperature is 35 °C, but can reach temperatures up to 56 °C at high-speed setting. Measuring 48 cm in height and 27 cm in width and breadth, the dehumidifier weighs only 6.5 Kg. The main components are air blower, desiccant wheel and motor, air heater, air-cooled condenser, water basin, power supply and a processor-based control unit. The operating parameters including heater temperature, heating rate, desiccant wheel rotation and air blower speed were pre-programmed and cannot be changed without triggering the safety routine that disables the appliance. Twelve grams of formulated catalyst was wash-coated on the desiccant wheel of the dehumidifier (Fig. 12.9-1b) to impart air purification function. The modified dehumidifier will be henceforth referred to as the Prototype Unit.

The performance tests conducted in the laboratory included comparison of airflow, noise and dehumidification data between the Prototype Unit and the original dehumidifier appliance. Test methodologies were designed with reference to the standard test procedures in ANSI/AHAM Standard AC-1-1988 published by the Association of Home Appliance Manufacturers (AHAM), but adapted to the available equipment. In addition, the reductions of VOC and bioaerosols by the Prototype Unit were measured by a new dynamic test method. It enabled the collection of real time performance data and direct monitoring of the appliance operation. The undergraduate students must obtain permission for field test from the University as well as the catering manager of the HKUST University canteen, the doctor of the public government clinic for elderly and the manager of the Home of Loving Faithfulness. Figure 12.9-2 shows the timeline of the phase two of the project.
Figure 12.9-1. Pictures of (a) dessicant-based dehumidifier and (b) dessicant wheel.

Figure 12.9-2. Project timeline for phase 2.

A. Laboratory Performance Data

Laboratory tests were conducted for airflow, noise, dehumidification and VOC remediation by the prototype.
12.9.1 Airflow and Noise Measurements

Airflow measurements were conducted to map the airflow distribution along the inlet and outlet of the prototype. This is essential for positioning of the sensor probes for transient monitoring of the temperature, humidity and VOC level at the prototype inlet and outlet. The students conducted the measurements at the laboratory of the Mechanical Engineering Department, HKUST after proper equipment training. The inlet and outlet airflow velocities were measured using VelociCalc Plus Multi-Parameter Ventilation Meter (Model 8386-M-GB) from TSI Inc. for blower speed settings of “normal-speed” equivalent to airflow of 1.33 m³/min (i.e., 48 scfm). The multi-point measurements along the air inlet and outlet (Fig.12.9-3) were obtained and tabulated in Table 12.9-1. It is clear from the results that uniform flow profiles were obtained at both inlet and outlet. This means that the sensor probe located at the central region of the inlet and outlet will give representative measure of the airstream conditions.

The noise level was also measured using Interacting Sound Level Meter (NL04) from RION for blower speed setting of “normal-speed” near the inlet and outlet of the Prototype Unit. The average noise levels are 23 and 48 dB at the inlet and outlet, respectively. These values are low compared to most air dehumidifier and air purifier appliances.

![Figure 12.9-3. Airflow measurement points along (a) inlet and (b) outlet areas of the Prototype Unit.](image)

| Inlet Air Velocity (m/s) | Outlet Air Velocity (m/s) |
|--------------------------|---------------------------|
| Position | A | B | C | D | E | F | Position | A | B | C | D |
| 1 | 1.07 | 1.11 | 1.03 | 1.04 | 1.12 | 1.01 | 1 | 5.31 | 5.42 | 5.29 |
| 2 | 1.06 | 1.10 | 0.98 | 1.05 | 1.12 | 1.03 | 2 | 5.27 | 5.47 | 5.33 |
| 3 | 1.04 | 1.10 | 1.01 | 1.02 | 1.11 | 1.04 | 3 | 5.37 | 5.41 | 5.36 |
12.9.2 Dehumidification Test

The dehumidification rate for the Prototype Unit was measured and compared with an unmodified dehumidifier. The Prototype Unit and dehumidifier appliance were placed in a 60 m² room with open windows. The test was conducted at an ambient temperature of 23 ºC and relative humidity of 80 %. The amount of water collected after 8 h was weighed and dehumidification rates of 0.14 Kg/h and 0.13 Kg/h were obtained for the Prototype Unit and unmodified dehumidifier, respectively. This indicates that coating the formulated catalysts onto the desiccant wheel does not significantly affect its dehumidification function.

12.9.3 VOC Removal and Remediation

Environmental test chambers are expensive and were not available for the tests needed in the project. It was decided that the Prototype Unit would be evaluated as a flow reactor. Ductworks were added to the air inlet and outlet to ensure uniform airflow and to prevent inadvertent mixing of the two airstreams. Figure 12.9-4 shows a schematic drawing of the experimental setup. The tests were conducted in a fume cupboard at ambient temperature (20-30ºC) and humidity (60-80 % RH). The VOC was evaporated and mixed with air before entering the inlet of the Prototype Unit. The inlet and outlet conditions were monitored in real time. The sensors used for the tests are VOC gas sensor Model Type D1 (#TGS 2602) from FIGARO, humidity sensor Model Ceramic SIL (HIH-3605-A) from Honeywell and temperature sensor Model DZ Version (LM35 DZ) from National Semiconductor. The sensor box was designed and built by with collaboration with an Electronic Engineering student at HKUST. The VOC sensors were calibrated against Photoionization Gas Detector Model PGM-30 from RAE using the target VOC. The humidity and temperature sensors were calibrated using VelociCalc Plus Multi-Parameter Ventilation Model (8386-M-GB) from TSI Inc. A set of VOC, humidity and temperature sensors was placed at the inlet and outlet of the Prototype Unit. A Digital Multi-Gas Monitor (1302) from Bruel & Kjaeror recorded the outlet carbon dioxide level. Continuous monitoring of VOC removal, temperature and humidity fluctuations and CO₂ generation were conducted with each experiment lasting 8 h. The data were collected at 1-second interval by a personal computer using PICO software.
The results of a four hours experiment are shown in Fig. 12.9-5 as an illustration. About 15 ppm of ethanol was evaporated and mixed with air drawn in from the surrounding. Figures 12.9-5a & 12.9-5b show that the inlet air temperature and relative humidity are constant at 23 ºC and 76 %. The inlet VOC level shown in Fig. 31c fluctuates between 12-20 ppm as the VOC liquid level changes during evaporation. The outlet conditions were monitored in real time and are shown in the figures. The outlet air temperature was 55 ºC and the relative humidity was 25 %. This is consistent with the normal operation of unmodified dehumidifier unit. The average outlet VOC level was 3 ppm and an average 75 % VOC removal per pass was obtained, which is equivalent to a removal rate of 42 mmole/h of ethanol. The carbon dioxide level increases from the ambient level of 300 ppm to 400 ppm at the outlet giving an average CO₂ production rate of 110 mmole/h, indicating a complete oxidation of ethanol to carbon dioxide and water. The amount of carbon dioxide detected at the outlet was higher than expected from the carbon balance and may be due to the oxidation of airborne microorganisms and organic aerosols present in ambient air.
Figure 12.9-5. Plots of (a) air temperature, (b) relative humidity and (c) airborne VOC at the inlet and outlet of the Prototype Unit.

Table 12.9-3 summarizes the results of the VOC removal and remediation tests conducted on the Prototype Unit. The results indicate that better than 75% per pass reduction can be obtained for VOC level less than 50 ppm. At least 50% reduction is obtained for concentrated VOC (> 50 ppm) airstream. The conversion rate depends on the VOC and its concentration. The Prototype Unit is very effective in removing odorous compounds such as Chinese incense and air freshener used in most Hong Kong household.

A small 3 cm x 3.5 cm section of the catalyst-coated desiccant wheel (25 cm diameter) was cut and placed in specially made holder shown in Fig. 12.9-6a. The piece of sample was tested in a 0.2 m³ environmental chamber at Chiaphua Industries Ltd. (Fig. 12.9-6b) for reduction of airborne VOC. The chamber was filled with the target VOCs through two stage saturators shown in Fig. 32b. Once the VOC level in the chamber stabilized, the fan was turned on to circulate the air through the sample. Three sets of sensors were located at the inlet and outlet of the holder, as well as in the center of the chamber. The chamber temperature and relative humidity were kept constant during the test. Figure 12.9-6c shows the results for VOC levels of 4000, 2000 and 1000 ppb at room temperature. The reduction rate was slower because of the low VOC concentration and the poor air circulation in the chamber. Also unlike the Prototype Unit, the catalyst was kept at room temperature throughout the test.
Nevertheless, fifty percent VOC reductions were achieved in the first fifteen minutes of the test.

Table 12.9-3. Prototype Unit field test performance for different volatile organic compounds

| Test VOC     | Concentration (gpm) | Percent removal per pass | Removal rate (mg/h) |
|--------------|---------------------|--------------------------|---------------------|
| Ethanol      | 20                  | 75                       | 30                  |
|              | 30                  | 85                       | 50                  |
|              | 100                 | 80                       | 150                 |
| Acetone      | 150                 | 60                       | 180                 |
| Benzene      | 150                 | 60                       | 180                 |
| Toluene      | 100                 | 60                       | 120                 |
| Ethylbenzene | 100                 | 95                       | 180                 |
| Thinner      | 400                 | 50                       | 380                 |
| Chinese Incense | 20            | 100                      | 40                  |
| Air Freshener | 20                 | 100                      | 40                  |

Figure 12.9-6. A small prototype unit (a) consists of a fan and coated monolith was placed in a test chamber shown in (b) and tested for VOC removal at ambient conditions. (c) The results show that the VOC level was decreased by half in less than an hour.
12.9.4 Bioaerosol Removal and Remediation

The germicidal properties of the nanostructured TiO$_2$ catalyst support was tested for Bacillus subtilis, Pseudomonas aeruginosa and Staphylococcus epidermidis. Circular pieces of filter papers (5 mm diameter) were saturated with distilled water (positive control); bleach solution (negative control), 75% alcohol and different concentration of TiO$_2$. The TiO$_2$ has similar germicidal effectiveness as 75% alcohol as shown in Fig. 12.9-7. This shows that the TiO$_2$ catalyst support exhibits intrinsic germicidal properties.

![Figure 12.9-7. Pictures of germicidal test for nanostructured TiO$_2$ for B. subtilis, P. aeruginosa and S. epidermidis.](image)

The intrinsic germicidal property of the TiO$_2$ support was also tested for natural indoor bioaerosol. A piece of cotton cloth was coated with a colloidal suspension of the nanostructured TiO$_2$. After drying, a circular piece of the cloth was cut and fitted inside the Andersen viable single-stage sampler in such a way
that air flows through the cloth before impacting on the collection plate. Tryptic soy agar (TSA) and malt extract agar (MEA) plates were respectively used for bacteria and fungi samplings. Two additional Andersen viable single-stage samplers were used to measure the ambient bioaerosol level and the amount of bioaerosol filtered by the cloth. The three samplers were operated at the same time and air samples were collected at 28.3 L/min for five minutes. The total bioaerosol level varied between 200 to 800 CFU/m³ during the test. Figure 34 shows that the cotton cloth filtered roughly ten percent of the airborne bacteria and fifteen percent of the airborne fungi. These values remained unchanged during the 1 h experiment. TiO₂ deactivates and kills microorganisms by direct contact. Nearly sixty percent reduction of airborne bacteria (Fig. 12.9-8a) was obtained from the TiO₂-coated cloth at the start of the test. This gradually decreases with time as the TiO₂ was slowly covered with dead microorganisms. Similarly, the forty percent reduction in fungi decreased to thirty percent at the end of the experiment (Fig. 12.9-8b).

![Figure 12.9-8. Plots of (a) percent bacterial reduction and (b) percent fungi reduction as a function of time for uncoated and TiO₂-coated, cotton clothes.](image)

Other components of the formulated catalyst were also tested for their germicidal properties. The desiccant is a good bactericide and cloth coated with the desiccant maintained a sixty percent reduction during the entire test as shown in Fig. 12.9-9a. The desiccant deactivates and kills the bacteria by rapid dehydration. However, this process is not as effective for airborne fungi (Fig. 12.9-9b).
Bioaerosol tests on the Prototype Unit were conducted for B. subtilis, P. aeruginosa and S. epidermidis. These are common airborne bacteria found in Hong Kong. The tests were conducted in a Class II Biological Safety Cabinet at the Applied Technology Center, HKUST. The cabinet was sealed with a plastic curtain and the blower was turned off during the test. Two fifteen millilitres of sterilized distilled water were aerosolised with a nebuliser to adjust the relative humidity inside the cabinet to 80% in order to minimize the evaporative effect on the aerosolised bacteria. The cabinet was kept at room temperature (i.e., 23-24°C) for the test. Ten millilitres stock bacteria culture solution (10^7 to 10^8 bacteria per ml) were aerosolised and uniformly dispersed inside the cabinet. Tests were conducted with the Prototype Unit turned on and off (i.e., control test). It is important to note that filter was not installed in the prototype during tests. Air samples were collected at various times using an Andersen viable single-stage sampler placed 60 cm from the Prototype Unit during the ten minutes test run and duplicate tests were carried out to establish reproducibility. The bacteria plates were incubated in a standard incubator at 37°C for 18 h. The bacterial colonies on each plate were counted as total colony forming unit (CFU).

The test results in Fig. 12.9-10 show a clear and immediate reduction in airborne bacteria when the Prototype Unit was turned on. Ninety percent reduction of B. subtilis, P. aeruginosa and S. epidermidis were reached at 1.5, 10 and 3 minutes of Prototype operation, respectively. The control experiments showed fluctuations due to poor circulation within the test chamber, but otherwise maintained a bacteria level higher than when the Prototype Unit was in operation.
After the experiments, the Prototype Unit was disassembled and the component parts were individually swabbed with sterilized cotton wools (4 cm$^2$). Each sample was stored in 1 ml sterilized distilled water in an eppendorf tube. 50 μl of sample was transferred to TSA and MEA plates. The TSA plates were incubated at 37 ºC for 24 h and bacterial colonies were counted. The number of fungal colonies was determined from the MEA plates after incubating at 30 ºC for 5 days. The results show no viable bacterial and fungal colonies were present in the interior parts of the Prototype Unit. Viable colonies are found on the external surface of the unit. This suggests that air passing through the Prototype Unit was sterilized by the action of the formulated catalyst.

### B. Field Performance Data

School canteens and public eateries where large number of peoples congregates often have poor air quality (cf. Table 12.6-6). Air quality survey of Hong Kong restaurants reported high VOC and bioaerosol levels. Also, strong odor from cooking is one of the main complaints. The HKUST canteen was selected as one of the sites for testing. The elderly and the young are vulnerable to the effects of poor air quality. Permission was obtained to conduct field test at a Hong Kong government public clinic for the elderly and at a charitable home for handicapped children. It is important to note that filter was not installed in the prototypes for these tests.
12.9.5 HKUST University Canteen

The bioaerosol removal by the Prototype Unit was tested for the reduction of natural bioaerosol (i.e., bacteria and fungi) at the HKUST University canteen during the peak lunch hours, daily for one month. The site has an average bioaerosol loading of 800 CFU/m$^3$, but values as high as 1200 CFU/m$^3$ are not unusual. About 90% of the bioaerosols are bacteria and 10% are fungi. Sixty percent of the bacteria are gram negative with close to forty percent having an average size between 1-2 microns. Only 10% of the bacteria have size smaller than 1 micron and the remaining 50% are larger than 2 microns. The common bacterial and fungi species are *Micrococcus*, *Staphylococcus epidermis*, *Cladosporium*, *Penicillium* and *Yeast*. Pictures of the canteen and the location of the Prototype Unit are shown in Figure 12.9-11.

![Figure 12.9-11. Pictures of the University canteen during the peak lunch hour. The location of test is shown by the red spot in Fig. 12.9-11c.](image-url)
A pair of Andersen viable single-stage samplers was located at the Prototype Unit’s inlet and exit to measure the reduction of bioaerosol. Sampling was done simultaneously at a sampling rate of 28.3 L/min for 5 minutes. TSA and MEA plates were used for sampling bacteria and fungi, respectively. Six measurements were carried out daily for bacteria and fungi. Typical results for a test run are shown in Table 12.9-4. The Prototype Unit maintained a better than 60% per pass removal and kill of airborne bacteria at loadings as high as 1200 CFU/m³. The average fungi reduction is 90% during the one month, field test. These values are comparable to most air cleaners equipped with high efficiency filter, but in this case the microorganisms were also killed.

Biweekly laboratory VOC removal and remediation tests were conducted using 10-15 ppm of ethanol. The VOC removal remained unchanged at around 80% per pass or 40 mmole/h.

| Measurement | In (CFU/m³) | Out (CFU/m³) | % Reduction per pass |
|-------------|-------------|--------------|---------------------|
| Bacteria    |             |              |                     |
| 1           | 1290        | 540          | 58                  |
| 2           | 860         | 300          | 65                  |
| 3           | 950         | 280          | 71                  |
| 4           | 1100        | 470          | 57                  |
| 5           | 780         | 370          | 53                  |
| 6           | 900         | 420          | 54                  |
| Average     |             |              | 60 ± 7              |

| Fungi       |             |              |                     |
| 1           | 110         | 10           | 91                  |
| 2           | 140         | 40           | 71                  |
| 3           | 180         | 10           | 95                  |
| 4           | 120         | 30           | 75                  |
| 5           | 150         | 40           | 73                  |
| 6           | 150         | 20           | 87                  |
| Average     |             |              | 82 ± 10             |

### 12.9.6 Public Clinic for the Elderly

Permission was obtained to conduct an on-site test of the Prototype Unit at a Wan Chai Public Clinic for the Elderly located at the second floor of Southorn Centre at Wan Chai, Hong Kong. The location is one of the busiest commercial areas in Hong Kong and the roadside air pollution index (API) for much of the year is “High”. The clinic occupied an area of 36 m² (Fig. 12.9-12a) and consisted of the doctor’s consultation room (12 m²), a private interview room (6 m²), and
m²) and an open space for the reception area and nurse station (18 m²). The clinic saw forty to sixty elderly patients everyday and was staffed by one doctor and four clerks and nurses. At any one time, there are on average 10 patients and 3 staffs at the reception area and 3 persons in the doctor’s consultation room.

The field test was conducted from May 2003, towards the end of the Severe Acute Respiratory Syndrome (SARS) outbreak in Hong Kong, until January 2004. The students taking part in the field tests were properly trained and equipped with medical safety equipment. Air samples collected at the reception area was designated as control samples (Fig. 12.9-12b). The Prototype Unit was located in the doctor’s consultation room (Fig. 12.9-12c) and was operated 10 h/day, 6 days/week during the six months test period.

Figure 12.9-12 (a) A drawing of the clinic floor plan, (b) picture of the reception area where control air samples were taken and (c) picture of the doctor’s clinic room where field testing of the Prototype Unit was conducted.

Five weeks air survey was conducted to determine the air quality at the clinic. The reception area has a lower bioaerosol loading of 300-800 CFU/m³ owing to better airflow and open floor plan. The doctor’s consultation room displays 2-to-3 times higher amount of airborne bioaerosol (i.e., 600-1400 CFU/m³) due to poor air ventilation. The airflow is roughly 0.1 m³/s, giving an overall air
exchange rate of about 1-2 per hour. The bioaerosol level at the reception area fluctuates from over 800 CFU/m³ during the opening hours in the morning and afternoon when most of the patients arrived for consultation to lows of 300 CFU/m³ during lunch break and closing time. Analysis of air sample identified eight bacterial species and seven fungal and yeast species. Micrococcus and Staphylococcus accounted for 85% of the airborne bacteria in the clinic. The remaining 15% belongs to the other five unidentified bacterial strains isolated from the survey. Further analysis was not conducted for fear that they may belong to virulent pathogens. Cladosporium, Pennicillium, Emmonsia and Yeast were detected in the clinic air. These bacteria and fungi are commonly found in Hong Kong.

Tables 12.9-5 and 12.9-6 summarize the results of the three months period when weekly measurements were conducted. The temperature and humidity of the clinic is relative constant at around 23 °C and 80%, but the bioaerosol level changes by the hour and day-to-day depending on the number of patients and outside air quality. The Prototype Unit was placed in the doctor’s consultation room and the airflow was set at normal-speed (Fig. 12.9-12c), allowing a complete exchange of the room’s air every 30 minutes. The air sample from the reception and doctor’s consultation room were sampled within 20 minutes of each other. The data in the tables show that the airborne microorganisms in the doctor’s consultation room remained higher compared to the reception area. However, this is a significant improvement when compared to the level when the Prototype Unit was not in use. Data obtained by measuring the inlet and outlet bioaerosol in the Prototype Unit indicated that 60% and 67% reduction in airborne bacteria and fungi was obtained, respectively. The performance was maintained during the six months test.

The doctor, nurses and clinic staffs reported a noticeable improvement of air quality in the doctor’s consultation room with the disappearance of odors associated with patients and disinfectants. There were also significant drop in doctor absenteeism due to flu and respiratory illnesses during the six months.

After the six-month field test, the Prototype Unit was disassembled and the component parts were individually swabbed with sterilized cotton wools (4 cm²). Each samples were stored in 1 ml sterilized distilled water and 50 μl of samples were transferred to TSA and MEA plates. The TSA plates were incubated at 37 °C for 24 h and bacterial colonies were counted. The number of fungal colonies was determined from the MEA plates after incubating at 30 °C for 5 days. The results of the test are shown in Table 12.9-7. The results show that bacteria and fungi thrived near the air intake where they deposited on the grills, panel and around the intake slots. However once the microorganisms are drawn through the catalyst-coated desiccant wheel, the number of viable
microorganisms decreases to zero. This further confirmed that the Prototype Unit is effective in removing and killing airborne microorganisms.

| Date (2003) | Reception (CFU/m³) | Consultation Room (CFU/m³) | Prototype Test (CFU/m³) | % Reduction per pass |
|-------------|--------------------|-----------------------------|-------------------------|---------------------|
|             | before             | after                       | inlet                   | outlet              |
| OCT 13      | 550                | 1200                        | 500                     | 210                 | 540                | 240                | 50                 |
| OCT 22      | 360                | 300                         | 250                     | 210                 | 80                 |
| OCT 27      | 800                | 800                         | 450                     | 800                 | 350                | 56                 |
| OCT 29      | 380                | 470                         | 250                     | 470                 | 170                | 54                 |
| NOV 08      | 510                | 500                         | 420                     | 500                 | 230                | 54                 |
| NOV 10      | 500                | 500                         | 200                     | 470                 | 190                | 60                 |
| NOV 12      | 740                | 780                         | 630                     | 700                 | 270                | 65                 |
| NOV 19      | 500                | 880                         | 890                     | 610                 | 100                | 54                 |
| NOV 26      | 650                | 720                         | 610                     | 690                 | 250                | 64                 |
| DEC 03      | 370                | 650                         | 510                     | 430                 | 180                | 58                 |
| DEC 10      | 420                | 710                         | 420                     | 420                 | 170                | 60                 |
| **Average** |                   |                             |                         |                     | 60                 |

Table 12.9-5. Prototype Unit performance for reduction of airborne bacteria.

| Date (2003) | Reception (CFU/m³) | Consultation Room (CFU/m³) | Prototype Test (CFU/m³) | % Reduction per pass |
|-------------|--------------------|-----------------------------|-------------------------|---------------------|
|             | before             | after                       | inlet                   | outlet              |
| OCT 13      | 65                 | 110                         | 56                     | 110                 | 35                 | 68                 |
| OCT 22      | 40                 | 56                          | 35                     | 66                 | 14                 | 75                 |
| OCT 27      | 28                 | 20                          | 14                     | 28                 | 7                  | 75                 |
| OCT 29      | 21                 | 21                          | 7                      | 21                 | 7                  | 66                 |
| NOV 05      | 21                 | 21                          | 14                     | 14                 | 7                  | 50                 |
| NOV 08      | 35                 | 50                          | 28                     | 70                 | 21                 | 70                 |
| NOV 10      | 56                 | 78                          | 56                     | 70                 | 20                 | 60                 |
| NOV 12      | 53                 | 70                          | 28                     | 63                 | 28                 | 56                 |
| NOV 19      | 50                 | 91                          | 35                     | 91                 | 35                 | 82                 |
| NOV 26      | 42                 | 57                          | 35                     | 57                 | 28                 | 51                 |
| DEC 03      | 42                 | 35                          | 28                     | 28                 | 7                  | 75                 |
| DEC 10      | 35                 | 63                          | 42                     | 35                 | 7                  | 80                 |
| **Average** |                   |                             |                         |                     | 67                 |

Table 12.9-6. Prototype Unit performance for reduction of airborne fungi.
Table 12.9-7. Viable bacteria and fungi found on the Prototype Unit

| Part No. | Part Description                  | Total Bacteria Count (CFU/m²) | Total Fungal Count (CFU/m²) |
|----------|-----------------------------------|------------------------------|-----------------------------|
|          |                                   | external | internal | external | internal |
| 1        | Blank Control 1                   | 0        | N.A.     | 0        | N.A.     |
| 2        | Blank Control 2                   | 0        | N.A.     | 0        | N.A.     |
| 3        | External Casing                   | 40       | N.A.     | 0        | N.A.     |
| 4        | Intake Grill                      | 120      | 20       | 40       | 0        |
| 5        | Intake Panel                      | 1300     | N.A.     | 20       | 0        |
| 6        | Intake Air slot 1                 | 40       | N.A.     | 0        | N.A.     |
| 7        | Intake Air Slot 2                 | 20       | N.A.     | 60       | N.A.     |
| 8        | Desiccant Wheel (inlet side) Q1   | 220      | N.A.     | 0        | N.A.     |
| 9        | Desiccant Wheel (inlet side) Q2   | 40       | N.A.     | 0        | N.A.     |
| 10       | Desiccant Wheel (inlet side) Q3   | 0        | N.A.     | 0        | N.A.     |
| 11       | Desiccant Wheel (inlet side) Q4   | 0        | N.A.     | 0        | N.A.     |
| 12       | Desiccant Wheel (outlet side) Q1  | 0        | N.A.     | 0        | N.A.     |
| 13       | Desiccant Wheel (outlet side) Q2  | 0        | N.A.     | 0        | N.A.     |
| 14       | Desiccant Wheel (outlet side) Q3  | 0        | N.A.     | 10       | N.A.     |
| 15       | Desiccant Wheel (outlet side) Q4  | 0        | N.A.     | 0        | N.A.     |
| 16       | Blower Fan Blade                  | 0        | 0        | 0        | 0        |
| 17       | Air Outlet 1                      | 0        | 0        | 0        | 0        |
| 18       | Air Outlet 2                      | 0        | 0        | 0        | 0        |

The Prototype Unit was cleaned and tested for VOC removal and remediation using 10-15 ppm of ethanol. The VOC removal remained unchanged at around 80 % per pass or 40 mmole/h. This indicates that the formulated catalyst remained active after a total of one-month laboratory test and six months of field study at the clinic. The Prototype Unit was given as a gift to the doctor for permitting us to conduct the field test at the clinic.

12.9.7 Charity Home for Handicapped Children

Four prototypes were built and tested during the months of September and October 2003. The new prototypes were tested and the performances for VOC and bioaerosol removal and remediation were within 90 % of the benchmark unit (cf. Table 12.9-3 & Fig. 12.9-10). Permission was obtained to field test two
of the Prototype Units at the Home of the Loving Faithfulness at Castle Peak Road, Sheung Shui. The Home is situated between two busy highways and next to a Tofu factory. Therefore, the particulate and bioaerosol levels at the site were high, and this was believed to be the main contributing factor in the high incidence of respiratory illnesses in the children. The two Prototype Units were placed at one of the children’s room (120 m²) shown in Fig. 12.9-13 and were operated 10 h/day for 7 days a week from May until September of 2004. The room houses ten children and only has one window-mounted, air conditioner that was turned on occasionally during summer nights, but more often windows were left opened and the fan was turned on. This means that the room temperature and humidity fluctuates depending on the weather. The temperature ranges between 22 to 33 ºC and the relative humidity was between 60 to 92 % during the three months measurement. Also, the particulate and bioaerosol levels can change dramatically from day to day.

Table 12.9-8 summarizes the results of field test conducted at the Home. The measurements were taken on two successive days with the windows open. Air samples taken next to the open window was used as control. Air samples taken at the middle of the room was assumed to represent the conditions of the room. The data shows that Prototype Unit was able to keep the airborne bacteria level in the room reasonable low compared to outside. Also, the Prototype Unit displays on average 52 % reduction per pass which is within the performance specification.

A slight drop in the performance was attributed to fouling due to the high particulate level. This was remedied by simply washing the desiccant wheel and by placing a coarse foam filter at the air intake. The Prototype Units were also disassembled and swabbed to check for viable bacteria and fungi. The result is similar to the previous Prototype Unit used in clinic. The number of viable microorganisms is higher at the air intake and close to zero at the desiccant wheel and air outlet.
Table 12.9-8. Prototype Unit performance for reduction of airborne bacteria.

| Date (2004) | Control (CFU/m³) | Children's Room (CFU/m³) | % Reduction for Children's Room | Prototype Test (CFU/m³) | % Reduction per pass |
|-------------|------------------|--------------------------|---------------------------------|-------------------------|---------------------|
| MAY 05      | 1100             | 500                      | 55                              | 500                     | 220                 | 58                  |
| MAY 06      | -                | 480                      | -                               | 630                     | 180                 | 71                  |
| MAY 18      | 950              | 550                      | 42                              | 470                     | 220                 | 53                  |
| MAY 19      | 1250             | 500                      | 60                              | 590                     | 180                 | 70                  |
| JUN 08      | 1200             | 570                      | 53                              | 700                     | 380                 | 48                  |
| JUN 09      | 850              | 580                      | 32                              | 750                     | 400                 | 47                  |
| JUN 16      | 750              | 300                      | 60                              | 1050                    | 470                 | 55                  |
| JUN 16      | 1200             | 930                      | 27                              | 750                     | 420                 | 44                  |
| AUG 02      | 820              | 572                      | 30                              | 650                     | 290                 | 55                  |
| AUG 03      | 650              | 570                      | 12                              | 530                     | 290                 | 45                  |
| AUG 16      | 640              | 500                      | 40                              | 490                     | 310                 | 35                  |
| AUG 17      | 540              | 420                      | 24                              | 530                     | 280                 | 48                  |

Average 62

12.10 CONCLUDING REMARKS

The project has successfully introduced important elements of entrepreneurship and product design in the final year design project as part of Chemical Engineering student education. The success of the project owed a lot to the excellent work of the undergraduate students, the participation of the various postgraduate, faculty, industrial partners and the support from the School of Engineering. The project is in part funded by the Hong Kong Innovation and Technology Commission (ITS/176/01C) to whom the author expresses sincere thanks.
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