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POLICY AND ENTREPRENEURIAL RESPONSES TO THE MONTREAL PROTOCOL: SOME EVIDENCE FROM THE DYNAMIC ASIAN ECONOMIES

by

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TABLE OF CONTENTS

RÉSUMÉ

Deux questions importantes sont analysées dans ce document technique: (i) comment les gouvernements des six économies dynamiques d'Asie - Hong Kong, Corée, Malaisie, Singapour, Taiwan et Thaïlande - ont répondu au defi posé par le Protocole de Montréal exigeant une réduction de leur consommation de produits tels que l'hydrocarbure chlorofluoré (CFCs) et le méthyle chloroforme (MC) qui détruisent la couche d'ozone; (ii) comment les firmes d'électronique situées dans ces économies ont résolu les problèmes techniques et autres causés par le remplacement du CFC-113 et du MC utilisés pour leurs opérations de nettoyage. Ce document montre de quelle manière les différentes stratégies de contrôle et les structures des politiques nationales peuvent influencer les incitations relatives à la conservation et au recyclage. Dans les pays où les restrictions quantitatives ont été appliquées la réduction de consommation du CFC a été importante. Dès la mise en place des quotas les gouvernements ont intérêt à élaborer un système de répartition des approvisionnements afin de bénéficier des rentes économiques provenant des quotas et financer ainsi les moyens affectés aux techniques d'assainissement. Des réductions substantielles résultant des mesures de conservation ont été réalisées, avec un coût supplémentaire relativement bas. Ce document montre également que les dispositions du Protocole de Montréal concernant les échanges ainsi que les taxes imposées par les États-Unis sur le CFC ont eu une influence déterminante sur les politiques gouvernementales et les pratiques de ces sociétés dont les économies sont surtout orientées vers l'exportation.

Ce document présente les principales alternatives de remplacement au CFC et, en se référant à une enquête sur le terrain, identifie certains obstacles d'ordre technique, informationnel et financier qui peuvent en retarder l'adoption. Parallèlement, il décrit comment plusieurs sociétés d'électronique ont surmonté avec succès ces obstacles. Si des progrès considérables ont été accomplis jusqu'ici, les coûts marginaux peuvent fortement augmenter durant le processus de substitution : en bref, les derniers 10 pour cent de réduction seront sans doute beaucoup plus difficiles à réaliser que les premiers 90 pour cent.

Des différences dans la durée de l'expérience et le niveau des capacités technologiques des sociétés dans divers pays influenceront de manière significative le degré d'initiative et d'innovation dans la recherche d'alternatives au CFC. En général les petites sociétés rencontrent plus de difficultés à cause du coût des équipements indispensables aux principales alternatives; de même, les firmes sous-traitantes dont l'activité est liée à la demande spécifique des clients, ont une marge de manœuvre plus limitée que les fabricants d'équipement pour s'adapter aux nouveaux procédés sans CFC. Néanmoins, pour l'ensemble des firmes utilisatrices, l'équation coût/bénéfice peut s'avérer plus favorable avec l'apparition sur le marché de nouvelles alternatives et avec l'augmentation du prix du CFC et du MC. A long terme la direction de l'innovation technologique ira très probablement vers la procédure "anti-nettoyage" du fait que les sociétés finiront par admettre que le nettoyage constitue une valeur ajoutée nulle au procédé. Ceci rejoint l'objectif visé, c'est à dire, "dégagement-zéro = déchet-zéro", une voie sur laquelle un grand nombre d'industries commencent à s'engager et qui, dans le cadre de l'environnement, s'impose comme le complément logique d'une production à "défaut-zéro."

SUMMARY

This Technical Paper examines: (i) how the governments of the six dynamic Asian economies — Hong Kong, Korea, Malaysia, Singapore, Taiwan, and Thailand — have responded to the challenge posed by the Montreal Protocol to reduce their

consumption of ozone-depleting substances like chlorofluorocarbons (CFCs) and methyl chloroform (MC); (ii) how electronics firms in those economies have coped with the technical and other problems involved in substituting for CFC-113 and MC in their cleaning operations. The paper shows how different national control strategies and policy frameworks can shape incentives for conservation and recycling; countries with quantitative restrictions in place have been highly effective in curtailing CFC consumption. Once quotas are in place, governments do well to devise an allocation system that enables them to capture the bulk of the quota rents to finance measures designed to facilitate the phase-out effort. Substantial reductions through conservation measures have been achieved at relatively low incremental cost. The paper also argues that the trade provisions of the Montreal Protocol and the US CFC tax have been important influences on the policy responses of governments and the practices of firms in these highly export-oriented economies.

The paper lays out the major options available for CFC substitution and, drawing on field research, identifies certain technical, informational and financial obstacles to their rapid adoption. At the same time, it illustrates how a number of electronics firms have successfully overcome these obstacles. While considerable progress has been made to date, marginal costs may rise more steeply as the substitution process proceeds: in short, the last 10 per cent reduction is likely to be far more difficult than the first 90 per cent.

Differences in the length of experience and the level of technological capabilities of firms in different countries strongly shape their degree of initiative and innovativeness in searching for CFC alternatives. In general, smaller firms face greater barriers to substitution due to high equipment costs associated with the principal alternatives; also, assembly contractors dependent on customer-dictated specifications have less flexibility in introducing new CFC-free processes than original equipment manufacturers. Nonetheless, the cost-benefit equation for all user firms is expected to become more favourable as new alternatives reach the market and CFCs/MC become dearer. In the longer term, the direction of technological innovation will almost certainly be towards `no-clean' processes, as firms have come to perceive cleaning as a zero value-added process. This is consistent with the goal of "zero emissions/zero waste" which firms have begun to pursue in a growing number of industries as a logical environmental complement to "zero defects" manufacturing.

PREFACE

The Development Centre, in its current research cycle, is examining the strategic choices and policy issues facing developing countries as they seek to cope with mounting environmental threats while sustaining economic growth. While coping with domestic environmental problems, however, countries are also confronted with a new set of global environmental challenges which call for their participation in a concerted international response.

The depletion of the protective ozone layer above the earth is one such challenge, to which the international community has responded with an historic initiative, the Montreal Protocol on Substances that Deplete the Ozone Layer. This international environmental agreement binds Parties to phase out their production and use of ozone depleting substances like chlorofluorocarbons (CFCs), halons, methyl chloroform (MC) and other chlorinated compounds. While the OECD Member countries account for the overwhelming share of production and consumption of controlled substances, some developing countries have become relatively large users. The six dynamic Asian economies (DAEs) — Hong Kong, Korea, Malaysia, Singapore, Taiwan and Thailand — are among this group, with their large, export-oriented electronics industries accounting for much of that use.

This paper examines the control measures the governments of the DAEs have deployed and their effectiveness to date. It also examines in some detail how electronics firms in those economies — foreign and locally owned, large and small — have been responding to the need to reduce their CFC and MC consumption. The practices range from the mundane to the truly innovative. The pace of reductions has been most dramatic where incentives for CFC substitution have been strongest but nowhere has innovative effort been wholly lacking. A general conclusion is that small and young firms, especially in the less technologically advanced of the DAEs, have the farthest distance to travel in mastering cleaning technologies based on CFC alternatives.

The experience of these six dynamic Asian economies should provide some useful lessons for developing country Parties to the Montreal Protocol, especially those with large electronics and metal cleaning sectors. Policy makers and corporate decision makers in those countries may benefit from knowing what factors help explain success in reducing CFC/MC usage in the DAEs and what measures may be required to assist their own firms in accelerating the phase-out of ozone depleting substances.

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President, OECD Development Centre
November 1991

I. INTRODUCTION

The Montreal Protocol on Substances That Deplete the Ozone Layer (hereafter, the MP) is a precedent-setting international agreement that entered into force on 1 January 1989, binding the more than 70 Parties to a strict timetable for phasing out the production and consumption of controlled substances known to damage the earth's ozone layer. Annex A substances (those in the original Protocol) consist of commonly used chlorofluorocarbons (CFCs) and halons; Annex B, added in June 1990, includes a number of other CFCs as well as carbon tetrachloride and methyl chloroform (1,1,1 - trichloroethane). Developed countries are bound to phase out all CFCs, halons and carbon tetrachloride by the year 2000, and methyl chloroform by the year 2005. Developing countries whose per capita consumption of the CFCs and halons listed in Annex A of the MP remains below 0.3 kilograms (known as Article 5 countries) are granted a grace period of ten years for implementing the phase-out schedule. Both the developed country phase-out schedule and the length of the grace period are to be reviewed at the next meeting of the Parties in October 1992. Given new scientific evidence on the extent of ozone loss over the northern hemisphere mid-latitudes[1], the probability is high that the phase-out schedule will be accelerated and the grace period shortened.

This paper examines the responses of six Asian newly industrialising economies (NIEs) — the Republic of Korea, Taiwan, Hong Kong, Singapore, Malaysia and Thailand — to the challenge of phasing out controlled substances. The focus is on the electronics industry, which is a major industry in all six economies and contributes a significant portion of their consumption of controlled substances. It should be noted at the outset that Hong Kong and Singapore are bound by the developed country phase-out schedule; Taiwan, while not a Party for political reasons, has announced its commitment to meeting the developed country phase-out schedule of the MP; Korea is not yet a Party but may well become one at the October 1992 meeting, with developed country status; Malaysia and Thailand are both developing country Parties. Malaysia, however, has set for itself the developed country phase-out target date of 2000. A country study is soon to begin in Thailand, which should help define that country's phase-out strategy more precisely.

The two controlled substances which are used most extensively in the electronics industry are CFC-113 (with an ozone depletion potential, or ODP[2], of 0.8) and methyl chloroform (MC for short, with ODP of 0.1). Both are chlorinated solvents used for the cleaning/degreasing of various electronic and mechanical components and subassemblies which go into electronic equipment. While CFC-113 is used principally in high reliability and high precision electronics applications, MC has a broader range of applications including the cleaning of metal parts. The principal emphasis of the discussion here is on the reduction of CFC-113 use in electronics cleaning.

By focussing on electronics firms' strategies and practices for CFC-113 and MC reduction, this paper seeks to identify: (1) the factors motivating the substitution efforts of specific firms; (2) the short- and longer-term control options being employed or considered for specific applications; (3) the technical complications of introducing certain CFC alternatives; (4) the capacities of different firms to cope with the challenge of CFC-113/MCA reduction. By taking a cross-country comparative approach, it is possible to relate national phase-out strategies and control policies to firm practices. Within any given country, it is also interesting to know whether reduction efforts differ systematically by firm characteristics (foreign-owned subsidiary as apposed to locally-owned; large versus small; subcontractor compared to original equipment manufacturer). The expectation is that the experience of these six Asian NIEs may provide some useful lessons for developing-country Parties to the MP with large electronics and metal cleaning sectors. Presumably policy makers in those countries would like to know what factors help explain success in reducing CFC/MC usage and what measures may be required to assist firms in accelerating their phase-out.

The paper proceeds as follows: The next section briefly summarises the policy framework and government initiatives to promote the reduction in use of controlled substances. Section III examines the experiences of firms with CFC-113/MC reduction, looking at both shorter term measures like conservation and recycling and longer term substitution. Section IV contains a brief discussion of the costs and benefits to firms of phasing out CFC-113 and MC. Finally, section V summarises lessons from the experience of these six Asian NIEs which may be relevant to other countries, especially Article 5 Parties to the MP.

II. POLICY FRAMEWORK FOR CONTROL OF OZONE DEPLETING SUBSTANCES[3]

While not all the six Asian NIEs are Parties to the MP at the present time, there is every reason to believe that all will make their best effort to comply with its provisions. Put differently, none of the six can afford not to abide by the terms of the MP. For the MP contains certain provisions restricting trade in controlled substances, products containing controlled substances, and perhaps eventually products made with controlled substances between Parties and non-Parties. All six economies are heavily export-dependent and the overwhelming share of those exports goes to developed country Parties to the Protocol — notably the United States and the EC. Moreover, electronics products represent a major export item (anywhere from 15 per cent to 25 per cent of total merchandise exports). Thus, their major electronics export markets could be threatened were they not to abide by the provisions of the MP. For most this means actually becoming Parties, while for Taiwan this option may not be open so it must simply act as a *de facto* Party and hope the *de jure* Parties recognise it as such.

Table 1 contains a summary of where each of the six Asian NIEs stands with respect to the MP and to the government's implementation of a CFC control strategy. Only Korea is currently producing CFCs, though a Taiwanese firm has completed construction of a production facility and may still commence production if it obtains the necessary (local) government approvals. The Korean CFC producer, Ulsan Chemical, has developed its own process technology for CFC production, with some assistance from the government's R&D laboratories. The Korean government has therefore been concerned that, if it were to join the MP, the country's investments in R&D and production capacity would not be totally wasted. At the same time, its search for alternatives is heavily conditioned by its earlier success in developing CFCs, with the result that it is focussing heavily on developing transitional substances (HCFCs) and other synthetic chemical alternatives.

Particularly noteworthy in Table 1 is that three of the six NIEs have introduced quantitative restrictions on CFC supply — in the form of import quotas set at 1986 consumption levels (as specified in the MP). While the other three have reporting and licensing requirements for CFC imports, production, and exports, they have not yet instituted quotas. With binding quotas in place, the governments of Hong Kong, Singapore, and Taiwan are faced with an allocation problem. How is the available supply to be distributed? Singapore has chosen to use a public tender to auction off half of the available quota in a given period. Since there are roughly 400 importers, distributors, and users eligible to bid, collusive bidding is not a problem. The first few rounds of bidding caused rapid escalation in effective CFC prices and provided strong incentives to conservation and substitution. Indeed, CFC prices have risen more steeply in Singapore than in any of the other economies. In addition, the government is able to capture the `windfall profits' or `quota rents' from the artificially induced scarcity, which would otherwise haved accrued to the CFC importers/distributors. Out of those rents it can subsidise recycling, information, and technical consultancy services to accelerate the CFC reduction effort. While Taiwan and Hong Kong have followed somewhat more conventional control strategies, they have also met with some success in phasing down consumption. Taiwan's government R&D laboratory is active in developing and diffusing CFC alternatives, but it apparently suffers from funding problems which would be alleviated if it could capture a share of the quota rents.

Table 2 shows the marked contrast in the CFC consumption trends between the three NIEs with quotas in place and those with no supply restrictions. Of the latter, Thailand has experienced the most dramatic increase in its CFC consumption over the last four years, reflecting principally the strong growth of its economy and of CFC-using sectors like refrigeration, mobile air conditioning, and electronics. Even so, per capita consumption is still the lowest in Thailand of all six economies. In terms of CFC-113 consumption, Thailand may soon overtake Malaysia, which has a much larger electronics industry in terms of the value of production and exports. By dividing consumption into the value of electronics exports, one can obtain a very rough picture of how efficiently different countries are using CFC-113 in electronics cleaning. The three NIEs with the effective quotas in place also have by far the lowest intensities of use (IUs) of CFC-113, suggesting there are strong incentives to conservation. By contrast, Thailand and Korea — the two with the highest overall CFC growth rates — also have by far the highest IUs of CFC-113. While these figures may be biased upward slightly for reasons explained in the footnotes to Table 2, the discrepancy in IUs is too large to ignore.

These data tell a dramatic story about the importance of putting quantitative restrictions in place if governments are to prevent CFC consumption from following the economy up into the stratosphere. Fortunately for the laggards, the costs of controlling CFC consumption are proving to be more modest than had been predicted on the threshold of the MP era. Still, there are both technical and financial hurdles to be overcome if alternatives are to diffuse widely throughout the electronics industries of the Asian NIEs. As more and more of the leading electronics multinationals move towards becoming CFC-free, it is becoming abundantly clear to small- and medium-sized firms in the region that they cannot afford to be too far behind. For, the centre of gravity of technological development in cleaning is decisively shifting away from CFC degreasers. Those who persist in their old ways may find themselves riding into competitive battle on a dinosaur.

Table 1: **Summary Information on Status of Six Asian NIEs vis-à-vis Montreal Protocol and Government Controls on CFCs**

	Party to Montreal Protocol	**Article 5 Country**	**CFC Producer**	**Quantitative restrictions on supply of CFCs**	**Government support for CFC reductions**
Korea	No	No	Yes	No	CFC Alternatives Technology Center/KIST
Taiwan	No	No	Possibly	Yes	Union Chemical Laboratories/ ITRI technical information and extension services
Hong Kong	Yes	No	No	Yes	Environmental Protection Dept. acts as information clearinghouse
Singapore	Yes	No	No	Yes	SISIR solvent recycling plant; consultancy services; database on CFC alternatives
Malaysia	Yes	Yes	No	No	
Thailand	Yes	Yes	No	No	

Source: D.C. O'Connor, 1991, *Strategies, Policies and Practices for the Reduction of CFC Usage in the Electronics Industries of Developing Asia,* Research Document, OECD Development Centre, Paris, June.

Table 2: **Selected CFC Consumption Figures for the Asian NIEs**

	Total CFC and Halon Consumption, 1986 (MT)	Percentage Change in CFC Consumption, 1986-1990	Consumption of CFC-113, 1989 (MT[a/])	Value of Electronics Exports, 1989 (US$m)	Intensity of Use[b/]
Korea, Rep.	11,632	+143	4,516	13,500	0.33[c/]
Taiwan	10,337	-34	2,011	12,500	0.16
Hong Kong	2,300	+4	1,628	11,200	0.15
Singapore	4,823	-14	2,800	15,300	0.18
Malaysia	2,597	+68	1,314	6,000	0.22
Thailand	2,520	+189	1,213[d/]	2,565[d/e/]	0.47[d/e/]

Notes: [a/] Consumption of CFC-113 is in ODP-weighted metric tonnes.

[b/] "Intensity of Use" is defined as metric tonnes of CFC-113 consumed per million US dollars of electronics exports.

[c/] Korea's domestic electronics market is relatively large by comparison with the others, so the consumption/exports ratio may somewhat overstate the intensity of use.

[d/] 1988 figures.

[e/] The electronics export figures for Thailand do not include miniature ball bearings which consume large quantities of CFC-113 in their cleaning. Their inclusion in Thai exports would reduce somewhat intensity of use.

Sources: Overall CFC/Halon consumption figures: UNEP, 1989, *Economic Options Panel Report*; For all countries except Thailand: export data are from GATT, 1990, *International Trade '89-'90*, Geneva; for Thailand, from the Thailand Development Research Institute (TDRI); data on changes in CFC consumption and on CFC-113 consumption level are from national government sources.

III. REDUCTION STRATEGIES AND PRACTICES OF ELECTRONICS FIRMS

Chlorofluorocarbon (CFC)-113 has come to be the solvent of choice in electronics cleaning for a variety of reasons. Besides being inexpensive, it has the following properties: (i) excellent cleaning effectiveness; (ii) low evaporation point; (iii) non-flammability; (iii) low surface tension; (iv) low toxicity; (v) noncarcinogenicity. CFC-113 can be used to clean a wide variety of electronic components without damaging their polymer, plastic, or elastomer packaging. It is seldom used in pure form but normally in azeotropic mixtures with some type of alcohol.

There are two major, two slightly less important, and a number of minor uses of CFC-113 in the electronics industry.

i. **Printed circuit board assemblies (PCBAs)**: The first major use is to remove flux residue from PCBAs after soldering. Flux is applied to the boards to enhance solderability of components, but if not removed flux additives like chlorides, fluorides, bromides, and halides can cause corrosion of metal interconnections and electro-migration. Failure to remove flux residue may also compromise electrical performance as well as hamper testing and inspection. CFC-113 is especially effective in removing fluxes with a high rosin (or `solid') content. There are two major types of PCBAs to which we refer in the ensuing discussion: through-hole plated boards, which are still the most widely used, and surface mount boards, whose use is rapidly expanding with the `laptop' revolution in personal computers and other trends towards greater and greater miniaturisation.

ii. **Degreasing of precision components**: The other major application is in the degreasing of a variety of electronic and precision mechanical components that go into electronics equipment. Some components may accumulate grease during production—e.g., stamped or machined metal parts may have grease applied to reduce friction during the machining operation. High purity electronic materials may accumulate dust, body oils, or other contaminants from handling or exposure to a `dirty' environment during transport, storage or production. Whatever the source, the contaminants need to be removed before final assembly and packaging of the components to ensure product reliability. Among the most important users of CFC-113 for degreasing of precision mechanical parts are hard disk drive (HDD) manufacturers, who use the solvent to clean the magnetic heads, head stack assemblies, head positioner bearings, etc. Other parts commonly degreased with CFC-113 are metal lead frames used in integrated circuit (IC) assemblies.

Other important users of CFC-113, who nonetheless account for a smaller portion of total consumption than the preceding two, are:

i. Makers of cathode ray tubes (CRTs) for computer monitors or televisions: The CRT contains a fine mesh screen called a shadow mask which fits just inside the phosphor-coated glass shell and through which electrons are fired by an electron gun. Many firms use CFC-113 to clean the shadow mask, especially for computer monitor CRTs, while some use it to clean the parts of the electron gun.

ii. Silicon wafer manufacturers: These raw materials for the semiconductor industry are ultra-pure and must be ultra-clean. The companies who slice the wafers from ingots, polish them and, in some instances, deposit an epitaxial layer on their surface must take great care that the wafers are free from particles of silicon dust or other contaminants before they are shipped to customers. While deionised (DI) water can remove loose particles, CFC-113 is often used to remove grease or other matter.

Still smaller quantities of CFC-113 are used in a variety of other applications, including:

i leak testing of IC packages and durability testing of IC package markings;

ii cleaning of screens used for PCB stenciling and for the application of solder paste to surface mount PCBs;

iii degreasing of bare printed circuit boards (PCBs) prior to assembly;

iv spray coating of certain PCBs and other parts;

v polishing of plastic moulded parts used in electronics products like telephones;

vi cleaning of watch movements;

vii cleaning of high frequency TV tuners;

viii cleaning of machine parts and tools during maintenance;

ix routine cleaning of workbenches and workclothes.

Methyl chloroform (MC) is normally used in cleaning operations where less stringent cleanliness standards apply. The following are a few examples of major applications for MC encountered in the six Asian NIEs:

i cleaning of the surface of IC and transistor packages prior to ink printing of the label;

ii cleaning of leads on transistors and certain ICs during plating or solder dipping operation;

iii cleaning of high temperature diffusion furnaces in semiconductor wafer fabrication facilities;

iv cleaning of ball bearing assemblies.

In some applications, especially metal cleaning, MC is a close substitute for CFC-113, so when the original MP went into effect and before MC was added to the list of controlled substances, a number of firms switched from CFC-113 to MC in such applications. For example, a number of disk drive manufacturers in Singapore switched to MC when supplies of CFC-113 began to be restricted. Most no longer consider using MC as anything more than a short-term transitional substance away from CFC-113 and some discourage any new applications.

Historically CFC-113 was so cheap and did its job so effectively, that there was little incentive to search for alternative solvents or cleaning methods. The cleaning of parts and components has generally been considered a low-cost, low-priority operation — a `necessary evil.' Since the MP, firms have begun to adopt a new perspective on cleaning. As CFC prices rise it is no longer such low cost, but it is still a low (or zero) value-added operation. This has caused a growing number of firms to ask if cleaning is really necessary, or can it eventually be eliminated. `No-clean' is becoming a widely shared objective of electronics firms, though one that is unlikely to be realised for a number of years at least.

Technological innovation is occurring rapidly in the development of alternative cleaning agents and processes. In the industrialised countries, there was widespread scepticism a few years ago about the feasibility of finding effective substitutes for CFC-113. As an article in *Chemicalweek* explains, "[f]ive years ago, [electronics makers] considered 113 irreplaceable as a solvent to remove residues and soldering flux from circuit boards. But today many products work as well or better, for specific needs."[4] A similarly rapid change has occurred with respect to CFC-113 use in metal cleaning, as illustrated by the case of IBM's disk drive factory in San Jose, California, which has converted from CFC-113 to a process using water and a saponifier, reducing CFC-113 consumption from 1,360 metric tonnes to 227 metric tonnes a year (or over 80 per cent) in only three years. As the manager of environmental programmes at the plant remarked recently, "[i]t's hard to imagine in 1991, but in 1987 this was a hotly debated issue of whether you could water-clean the parts."[5]

How fast are these new technological options diffusing to electronics firms in the six Asian NIEs and through what channels? What role are domestic firms playing in fostering technological innovation in this area?

1. Process Characterisation: Vapour Degreasing

To lay the groundwork for responding to these questions, it may be helpful first to characterise the most pervasive process technology using CFC-113 for solvent cleaning. This is known as vapour degreasing, which utilises one of two basic equipment configurations—a tank-type (or batch) degreaser or an in-line conveyorised degreasing/cleaning machine. In the former case, components or circuit boards are immersed in a CFC-113 bath covered by a vapour blanket. The tank degreaser normally has two sumps, a boiling sump and a distillation sump. In some cases ultrasonic generators are built in to enhance cleaning effectiveness, especially for very small components which are not damaged by certain ultrasonic frequencies. Used solvent accumulated in the boiling sump is sometimes recovered for reuse in a secondary, external still. The parts are scrubbed in the heated liquid solvent by the boiling action (and ultrasound), then moved to just above the boiling sump where the liquid solvent is vapourised. Next, they are rinsed in a cooler solvent in the distillation sump, then placed in a pure solvent vapour blanket above that sump. Finally, the parts are raised to the vicinity of the cooling coils [just below the `freeboard' zone (defined below)], where the condensed solvent drips back into the distillation sump.[6] In the case of in-line degreasers, the parts/boards are passed through solvent cleaning and rinsing chambers on a conveyor, with the cleaning machine sometimes directly connected to the back end of the wave solder machine or infrared (IR) reflow oven in a continuous flow process. In this case, the cleaning system is open only at one end, where the cleaned parts are off-loaded.

In either type of system, a major source of solvent loss is the `drag out' of solvent with the components as they are removed from the degreaser (see Figure 1). Since, as already indicated, one of the advantages of CFC-113 from the user's perspective is its low evaporation point, evaporative losses can also be very high. They are especially significant in the case of tank-type degreasers, since the lids are normally removed during use. Another possibly serious cause of evaporative losses is known as `work shock,' which results when a workload introduced into the vapour blanket causes the blanket to collapse, allowing air into the degreaser. As the vapour blanket is restored, the vapour-laden air is pushed out and high emission losses occur. Even in closed systems, there may still be some evaporative loss through worn seals and gaskets on pumps, valves, panels and pipe joints. Solvent spillage either in transport or during topping up of degreasers results in still more losses. The emission losses through these various means, when there is no effective vapour capture system to prevent escape into the outer atmosphere, contribute to the destruction of the ozone layer.

The process characterisation just described for CFC-113 as well as the major sources of evaporative losses are virtually identical for MC.

2. The Technical Options for CFC-113/MC Reduction

There are a number of technical options firms have at their disposal as they devise control strategies. The options vary in technical efficiency according to the particular application. They differ in cost effectiveness as a function of such factors as size of operation (as measured by production volume). Also, firms may encounter steeply escalating marginal costs of substitution for CFCs beyond some threshold, i.e., after the `easy' alternatives have been exhausted. In this sense, an unresolved technical problem appears to the individual firm as a steeply rising short-run incremental cost curve.

First, we enumerate the major short-term conservation and control measures adopted by the firms studied.[7] Then, we look at the medium-term substitution strategies and practices of a number of different types of CFC-113/MC user firms. Finally, we consider how the adoption of the alternative technologies has affected the production costs and competitiveness of adopting firms.

a. Conservation measures and in-house recycling

The most immediate ways in which firms can reduce CFC-113 consumption are through better housekeeping procedures and engineering controls. These are measures aimed at reducing wasteful consumption of CFC-113, loss through spillage and leakage, drag out of solvent with work pieces, and evaporation of the solvent at various stages in the process. The majority of the firms sampled were employing some conservation and control measures. Firms cited solvent reductions ranging from 20-40 per cent resulting from the adoption of such measures. An average reduction of 25 per cent from such measures seems a conservative estimate.

Among the most widely encountered conservation measures[8] are: retrofitting degreasers with additional recondensation (cooling) coils; detecting and repairing leaks; keeping batch degreasers covered when not in use and replacing hatch-type lids with sliding ones; consolidating workloads to optimise the utilisation of degreaser capacity; redesigning baskets to minimise the `piston effect' which forces vapour out of the degreaser; reducing drag out through better control over temperature cycling and the insertion and withdrawal velocity of work pieces; controlling blow-off air velocity. In most cases, conservation was the first step taken by firms to reduce CFC consumption; in some cases it has been followed by other measures but not in all. In general conservation measures involve at most only modest investments and are likely to be justified on the basis of net cost savings to the firm. Moreover, they do not require sophisticated technology. Retraining of technicians and operators is the critical requirement for their successful adoption. CFC/MC suppliers as well as cleaning equipment vendors often provide advice on better housekeeping practices and engineering controls.

For subsidiaries of multinational firms, the initial impetus to introduce conservation measures often comes from their parent companies, many of whom have set company-wide phase-out schedules well in advance of the MP timetable for the developed countries. Multinational subsidiaries are normally allowed considerable discretion by their parents in devising better housekeeping procedures, since they are in the best position to initiate such changes, which in any case usually do not involve the actual substitution of alternative cleaning methods for CFC cleaning. In the event that engineering controls involve significant process modifications (which in turn require detailed evaluation), they are more likely to be initiated by headquarters or the firm's research and development (R&D) laboratory. At the very least, customer acceptance is likely to be required, whether the customer is the parent company, an independent firm, or the US military.

[Figure 1 : Solvent losses in a typical printed wiring assembly plant]

The motivation for firms not bound by global corporate policy to adopt conservation measures is less evident, especially in countries where there are few restrictions on CFC supply. Admittedly there may be cost savings associated with reduced CFC-113 usage, but where the CFC-113 price has not been bid up by supply quotas the cost savings would be modest at best. In all six Asian NIEs, firms have been forewarned, either by the government or by trade associations, of the possibility of CFC shortages and escalating prices in the future. Expectations would appear to be shaping conservation strategies on the part of many firms, even where actual prices still remain relatively low. Since knowledge of simple conservation measures is now widely diffused and their benefit/cost ratio almost certainly favourable, firms would be irrational not to try to reduce CFC consumption.

The capture and recycling of used solvent is another option firms have for reducing `virgin' CFC-113 usage. In Singapore, 13 of the largest 25 CFC-using electronics firms have invested in in-house recycling, with almost all those investments occurring in the second half of the 1980s, when controls on the `virgin' CFC supply were imminent if not already in effect. Those firms have reported CFC savings of 10-30 per cent through in-house recycling.[9] A sizeable number of firms interviewed in the other five countries also practice in-house recycling. Several had distillation units built into their degreasers while a few had additional stand-alone systems for off-line recycling of dirtier solvent (the `still bottoms'). A number mentioned rising CFC prices as a major incentive to recovery of used solvent.

b. Alternative cleaning agents and methods

Conservation may be effective in achieving initial reductions at low marginal cost, but beyond some point further reductions from this source are difficult to achieve. Even if a firm has reduced consumption 30 per cent by this means (and perhaps another 20 per cent by recycling), the bulk of reductions must come from elsewhere if a complete CFC phase out is to be achieved. This requires either the adoption of alternative cleaning methods, which has been the more common approach, or the elimination of cleaning altogether.

First, let us review some of the more widely available options for firms seeking technically feasible and economically efficient alternatives to CFC-113 use in electronics cleaning.

i alternative solvents: alcohol-based solvents, especially isopropanol (IPA), acetone, and ethyl acetane; CFC-113 azeotropes, which consist of blends with IPA, acetone, methanol, or methylene chloride [e.g., Freon SMT (ODP = 0.552), Freon MCA (ODP = 0.52), Freon TMC (ODP = 0.404)]; hydrocarbon/surfactant blends (e.g., terpene-based blends); HCFCs (classified as transitional substances under the revised MP);

ii aqueous and semi-aqueous cleaning: the former using pure water (de-ionized or reverse osmosis), possibly in combination with a saponifier when the flux contains resinous materials; the latter using a combination of pure water and an organic solvent like terpenes or alcohol;

iii `no-clean' processes: immediately available options include use of low solid or RMA (rosin, mild activated) fluxes; longer term development of inert atmosphere soldering.

As compared with conservation measures, most of these CFC alternatives are considerably more costly. Alternative solvents like CFC-113 azeotropes and HCFCs are generally more expensive. For example, in Thailand Freon SMT can cost three times as much as pure CFC-113. The alcohol-based products and terpenes are normally cheaper than CFC-113 but are not close substitutes in all applications; in some cases firms have been reluctant to adopt them because of their inflammability and, in the case of terpenes, their noxious odour. Ironically, inflammable solvents which were once rejected on safety grounds are now being re-considered as CFC-113 substitutes. The environmental control and safety engineer at one Malaysia-based semiconductor firm indicated that, after six months of searching for a `safe' solvent with similar properties to CFC-113, the company has begun evaluating an inflammable substance. Nevertheless, since electronics firms have long utilised various inflammable substances for which they have had to introduce special safety precautions and fire control systems, it is doubtful whether the use of inflammable solvents would pose intractable control problems.

As new soldering and cleaning products reach the market at an accelerating pace, one concern is whether and to what extent they may compromise product quality and reliability. Traditionally, a way of ensuring reliability has been to require that products conform to the standards set by the US Department of Defense (DOD) (so-called `mil specs'). Even commercial electronics suppliers frequently require that their suppliers meet `mil specs.' Until very recently, the DOD's quality assurance specification required CFC-113 cleaning of printed circuit board assemblies.[10] Now, the in co-operation with the Environmental Protection Agency (EPA) and the Institute for Interconnecting and Packaging Electronic Circuits (IPC) — an industry standards body US DoD, has introduced a programme of benchmark testing of alternative cleaning products and processes. They are evaluated against the results of the standard CFC-based cleaning agent, which is a nitromethane-stabilised CFC-113/methanol azeotrope (or Freon TMS). The US military standard on soldering has recently been replaced with MIL STD 2000, rev.A, which discourages use of CFC-113 and allows the use of alternative solvents which have been proven effective by the benchmark tests. A number of alternatives to CFC-113 for use with rosin fluxes and solder pastes have already passed Phase 2 benchmark testing; they include:

- Gensolv 2004 and Gensolv 2010 (HCFC substitutes made by Allied Signal);

- KCD-9434 (an HCFC substitute made by DuPont);

- Bioact EC7 (a semi-aqueous, terpene-based substitute made by Petroferm);

- o Axarel-38 (a semi-aqueous substitute made by DuPont);
- o Marclean-R (a semi-aqueous substitute made by Martin Marietta);
- o Ionox MC (a semi-aqueous substitute made by Kyzen);
- o Freon SMT (a diluted version — azeotrope — of CFC-113 with lower ODP made by DuPont).

Another product reportedly close to approval is DuPont's Axarel-32.[11] Phase 3 of the testing programme is intended to qualify water soluble fluxes and solder pastes, `no-clean' fluxes and solder pastes, and controlled atmosphere soldering processes. The IPC has agreed to maintain a cumulative compatibility list for each alternative that passes the benchmark test.

An in-line aqueous cleaning system requires a sizeable capital investment, which can be as high as a quarter of a million US dollars and normally not less than $100,000. In Taiwan, a CFC-113 in-line degreaser costs only 70 per cent as much as an aqueous cleaning system. If a firm must also invest in a de-ionized (DI) water plant, this can substantially raise the total investment; in Thailand for example, a DI water facility costs around $120,000. In addition, firms need to invest in waste water treatment to remove heavy metals before discharge. The water soluble fluxes used in conjunction with aqueous cleaning systems are more expensive than standard rosin fluxes (by a factor of 3.3 in Taiwan for example), but even so overall material costs may be lower due to cost savings from the elimination of CFC-113. In some cases firms have employed `no-clean' very low solid fluxes (1-10 per cent solids as opposed to the normal 15-35 per cent solids), theoretically eliminating the need for post-solder defluxing. While `no-clean' fluxes are even more expensive than water soluble ones, it is possible that the higher flux cost can be more than offset by the reduced flux use and the elimination of one process step. A small amount of flux residue is normally left following soldering with `no-clean' fluxes. If a firm should choose it can remove the residue through aqueous cleaning, but in so doing it negates any expected cost savings of a `no-clean' process.

As for semi-aqueous cleaning systems, not only are they more costly than straight aqueous systems (a semi-aqueous cleaner can cost in excess of $180,000) but the range of full in-line equipment currently available on the market is still limited. The inflammability of certain semi-aqueous cleaning agents also calls for adequate investment in fire suppression systems. These factors are reflected in the relatively low adoption rate of semi-aqueous processes among firms in the six Asian NIEs. In Taiwan, a survey of 29 electronics firms which either have changed or are considering changing their defluxing process found that only three were considering semi-aqueous cleaning (none had actually switched to this method).[12] By contrast, ten had already converted (five completely, five partially) to aqueous cleaning, while eight were using a `no-clean' flux, four `no-cleaning' (presumably with a rosin flux), and another four other solvents. Interestingly, in Korea where very large firms dominate the electronics industry, the two industry leaders (Samsung and Goldstar) have installed one semi-aqueous terpene-based cleaning system each. At least one other firm — a Japanese-Korean joint venture — has also installed such as system.

The use of alternative solvents is quite widespread among the firms interviewed. As previously noted, a number had already switched from CFC-113 to MC, which is virtually a drop-in substitute: one contract assembly house in Thailand found that with minor modifications to its CFC degreasers they could be used with MC, which is only half as expensive as CFC-113. Substitution with MC appears to be especially attractive to smaller firms, not only because of the material cost savings but also because they can avoid making major new equipment investments. Many firms, large and small, are using CFC-113 azeotropic blends like Freon SMT.

Before reviewing the case evidence from firm interviews and factory visits, a few general observations about the nature of competition in the electronics industry may be useful. First, given the extreme importance accorded product reliability in the professional electronics market (whether for military or commercial applications), electronics manufacturers cannot afford to compromise the cleanliness of their products; it is a matter in many cases of competitive survival. Any reliability problems with a firm's products could lead to the loss of major customers' business. Furthermore, in the case of component or PCB assemblers, substitution away from chlorinated solvent cleaning is likely to require the prior consent of key customers. Not to gain that consent is to risk loss of valuable contracts. These considerations help explain the traditional conservatism of many electronics firms with respect to process modifications (the `if it ain't broke, don't fix it' syndrome). The negative side of this, from the perspective of dynamic efficiency, is that when firms are simply content to keep a process running smoothly, they may overlook important potential sources of cost savings.

Semiconductor firms

Already, many multinational semiconductors firms which had been using CFC-113 or MC for cleaning the surface of IC packages prior to marking have switched to other solutions. The IC assembly operations visited were mostly Japanese or US-owned multinationals; one was a Hong Kong-based subsidiary of a European multinational; another a Thailand-based affiliate of a Hong Kong contract assembly house. The most widespread alternative adopted appears to be the use of isopropanol (IPA) for cleaning the plastic package surface. A US semiconductor firm in Malaysia has been able to use IPA and acetone in its freon degreasers (without the application of heat), so like MC they too appear to be drop-in substitutes. Another US subsidiary in Malaysia has found it can apply a primer coat to ensure adhesion of the transfer printed marking (see Box 1).

Box 1: Cleaning IC Packages at AMD (Penang)

Advanced Micro Devices (AMD) is a US semiconductor firm with large assembly and testing operations in Malaysia. Traditionally, it used Freon Tf/Arklone P for cleaning the surface of its IC packages prior to marking. Then, with the MP, it embarked on a substitution programme. Initially, it had planned to wait for the commercial availability of an HCFC-based solvent. To avoid delays however, it experimented with Primer 910s, an alcohol-based solvent belonging to the silane family, starting with its plastic products (dual-in-line and leadless chip carriers).

Primer 910s is applied to the package using a gravity-feed fixture and an applicator attached to the front-end of the marking machine. The system was designed by local plant engineers. The use of Primer 910s saves the floor space of the freon degreaser as well as some processing time. When the new process was first introduced in the 2nd quarter of 1988, there were problems with mark permanency. It was found that pre-heating of the packages ensured proper drying of the Primer prior to marking, enhancing durability. Even so, this method is reported to be less effective than Freon Tf/Arklone P, so presumably further process improvements are still being explored.

—Based on an article prepared by Jariyah Hashim of AMD (Malaysia), dated 18 October 1991.

Another, more innovative approach has been devised by the Hong Kong subsidiary of a US semiconductor firm. In this case, the switch to an alternative cleaning method was part of a larger reorganisation of its production process. Traditionally, marking had been performed after final testing; then, the order was reversed so that less grease and dirt would accumulate on packages prior to marking. From the front-end of the testing operation, marking was then transferred to the back-end of assembly. The next step was to mark the packages immediately after moulding and curing, before the encapsulated devices had been separated from one another by trimming their metal leads. In this way, the packages can be fed into a marking machine in batches rather than as individual units, increasing throughput. At the same time, moving marking still further forward in production reduces grease and dust contamination even more. Then, to degrease the devices prior to marking the firm chose a novel approach: in place of solvent cleaning, the moulded packages are passed quickly under a hydrogen flame. The three processes are now performed in-line in an integrated module: hydrogen flaming, marking, lead trim and form.

While this approach is slightly more automated than those based on primer or IPA cleaning, hence somewhat more costly, all represent relatively low cost alternatives to pre-marking CFC degreasing. A more capital intensive approach to marking has also been gaining acceptance:— laser marking. Thus far however, for technical as well as economic reasons, diffusion of laser marker systems has been limited. Technically, the major shortcoming is that the laser marking is not as legible as ink marking. One way of enhancing contrast is through changing the package surface from a matte finish to a shiny one, which in turn requires mould conversion.[13] For certain products, the low contrast is a liability. Thus, the Malaysian-based subsidiary of a large Japanese company has switched to laser marking in most products but still uses ink for marking its memory ICs, although it is currently qualifying a laser marker for this line. The major economic drawback is the high cost of a laser marking system. One laser marking machine sells for approximately $370,000 in Malaysia. Interestingly, while the `guts' of the machines used in the Malaysia-based Japanese firm—the laser printer mechanisms—are made in Japan, other parts—like fixtures for automatic loading/unloading—are locally designed and made.

The European multinational assembling semiconductors in Hong Kong has also introduced laser systems extensively in its marking operation, including for surface mount transistors. Only in the case of the SOT-54 transistor, which requires a body coating, does it still clean with a chlorinated solvent, in this case MC, which coats at the same time that it cleans. This amounts to only about 5 per cent of production volume. The same firm still uses MC for degreasing metal lead frames before plating, but it has plans to install an aqueous cleaning system with ultrasonics to eliminate MC use in that process within one year.

Metal lead frames are a key component of semiconductor devices which typically require degreasing before silicon die are attached to them. Normally the degreasing is performed by the lead frame supplier. Traditionally, however, semiconductor firms have also cleaned incoming lead frames as an added precaution. One major US customer for lead frames in Malaysia decided to evaluate the effects of eliminating incoming cleaning. On the basis of a number of parameter checks, there appeared to be no significant differences between those lead frames it cleaned and those it did not. Since the supplier is located in the vicinity of its own plant, it also tracked the cleanliness of lead frames in its supplier's plant for a few months. The supplier, meanwhile, partly in response to queries from customers about the quantity of CFC used in cleaning its lead frames, decided to switch to acetone. Even with the precautions taken, the lead frame buyer still had to obtain the permission of the two major customers for its components before it could eliminate incoming lead frame cleaning process.

Only two semiconductor wafer fabrication facilities were visited during the field research for this study, both in Taiwan. It appears that these facilities are relatively small users of controlled substances. The main application of CFCs is not in solvent cleaning but in the chiller systems for the fab areas (CFC-11). In addition, some CFC-13 is used in one firm's plasma etcher, but the US etcher manufacturer has found a drop-in replacement and is working with the Taiwanese firm to make a smooth transition to the new substance. Both firms use MC to clean the quartz tubes in their diffusion furnaces; since the furnaces are heated to above 1,000° C., the MC should decompose and not contribute to stratospheric ozone depletion. Nevertheless, even if the firms could receive credits for incineration, they would still need to explore alternatives since MC will not be available indefinitely.

Printed circuit board assemblers/professional electronics equipment manufacturers

Cleaning/defluxing of assembled printed circuit boards (PCBs), as noted above, is one of the most common uses of CFC-113. In general, manufacturers of simple consumer electronics products like radios and televisions do not need to use CFC-113 in cleaning their PCBs. These products do not have to be made to very strict specifications; product reliability is not as crucial as in military electronics, telecommunications, or computer systems. The focus here therefore is on firms engaged in professional/industrial electronics board assembly.

Among such firms in the six Asian NIEs, there is widespread interest in aqueous cleaning systems as well as more limited interest in semi-aqueous cleaning and `no-clean' processes. As yet, however, the number of systems installed is small relative to the potential market. Unlike a substitute solvent, for which a modification to an existing degreaser may be the only process change required, with aqueous cleaning a thorough equipment substitution and process modification is involved. Firms introducing a new process generally have to move down a learning curve whose lower asymptote corresponds to a smoothly functioning process (with few surprises). A new board cleaning process can introduce uncertainties—require adjustments elsewhere in the process, reduce yields, cause costly production delays as re-learning occurs, etc.—all with no guarantee that the product will still meet customer specifications at the end of the day. A firm with a sufficiently high volume can afford to switch a single line over initially to aqueous cleaning and evaluate the results before making a large-scale commitment to the alternative. For a small firm, even one whose volume is sufficient to justify one aqueous system, the risk of converting all production from solvent cleaning to aqueous cleaning may seem unacceptably high.

There are still a number of application-specific technical complications to be ironed out with aqueous systems, most of which are only in their first generation. These are virtually unavoidable with any new technology, and there is nothing to suggest that they will prove insurmountable. Since the large multinational firms are in a somewhat stronger position than many small local firms to finance the fixed investments and to absorb the risk of experimenting with untried technology, the latter appear inclined in many cases to play a waiting game. Presumably if they delay long enough, they can benefit from equipment and process redesign in a second or third generation of aqueous cleaning systems. Nevertheless, even some relatively small firms have shouldered the risk of adopting aqueous cleaning, perhaps out of concern to reduce quickly their contribution to the ozone layer problem but perhaps (also) with an eye to gaining `first mover' advantages over their laggard competitors.

Aqueous systems are quite commonplace in the Asian NIEs for cleaning through-hole PCBAs. Water soluble fluxes have been developed that can be used effectively in conjunction with aqueous cleaning systems. Aqueous cleaning is still not widely used for the newer generation of PCBAs known as surface mount assemblies (SMA) (where components are soldered to the surfaces of the board). The technical problems to be solved here are especially daunting. One major difficulty is ensuring that a water-based system can clean the flux residue from the very tiny spaces under low stand-off components effectively. Even if water could work its way into the tiniest niches and crevices, it cannot so easily be removed. In the case of some components, water may seep inside the package and cause damage. Fine pitch components commonly populating surface mount boards (i.e., those with very small spaces between their lead centres) also pose cleaning challenges for water-based systems.

Ironically, the more sophisticated the electronic product technology becomes, the more difficult it becomes to find effective alternatives to CFC-113 cleaning. None of the problems is insurmountable, though some may take more time and greater resources to solve than others. High pressure, low flow rate oscillating water jets may be able to clean effectively in tight spaces. Post-cleaning, air knives can remove excess surface liquid; hot air blowers or infrared dryers should evaporate any remaining moisture. Should further drying still be needed, as it sometimes is, at least one firm has introduced hand-operated compressed air guns at the end of the line. As for seepage, one contract assembler in Thailand using an aqueous cleaning system for the drive controller boards it assembles for a large disk drive manufacturer found that the water was entering a hole in the housing of the spindle motor mounted on the board; the customer was able to redesign the component to eliminate the hole. Firms have also had to examine moulding compounds used for plastic IC packages and hermetic seals on ceramic IC packages more closely to ensure that water cleaning would not result in seepage and component damage. The use of de-ionised water to clean aluminium parts can cause etching, a particular concern with ceramic IC packages common in military applications.

To be able to use an aqueous cleaning system with surface mount technology (SMT), it is necessary to employ a solder paste containing a water soluble flux. While water soluble fluxes for wave soldering of through-hole boards are readily available, effective water soluble solder pastes for IR reflow soldering of surface mount boards have not until recently been widely available in the market. New solder pastes for SMT have been developed with a view to the following desirable properties: (i) tack time: components mounted on the board must be held in position until the IR reflow process (rosin normally provides the desired tackiness, but these solder pastes have low rosin content); (ii) printability: it should be possible to apply the paste uniformly with a stencil printing process; (iii) reflow profile: clearly defined parameters for temperature cycling compatible with existing IR reflow ovens (which typically cost around $50,000 each); (iv) water solubility; (v) non-corrosivity in the case of `no-clean' products. Products with these desirable properties have begun to appear on the market, but adequate time has not yet elapsed to permit their thorough evaluation on surface mount product lines, at least by most firms interviewed. Besides, they have yet to be qualified as CFC-113 substitutes under Phase 3 of the joint DoD/EPA/IPC benchmark testing programme mentioned above.

One contract PCB assembly house in Thailand uses an aqueous cleaning system with a water soluble flux for its through-hole board assemblies, but continues to use CFC-113 to clean surface mount assemblies, which represent a rapidly growing share of its output. Interestingly, the company has acquired a US firm which was a pioneer in SMT and has entrusted it with responsibility for evaluating new water soluble solder pastes for use in aqueous cleaning of SM boards. The US affiliate can test out the pastes in its own IR reflow ovens, without the Thai facility's having to sink capital before the new process is proven.

Some industrialised country firms, notably in Sweden, appear to have advanced quite far towards finding solutions for surface mount assemblies. The intensive search in Sweden no doubt owes much to a government regulation prohibiting use of CFC-113 for electronics and metal cleaning by the beginning of 1991 (with a few minor exceptions, mostly military applications) and use of MC by 1993. One major Swedish electronics firm reportedly uses a halide-free, non-corrosive solder paste for its surface mount assemblies, leaving the residue on the boards. While comprehensive information is not available on current best practice for surface mount assembly in other industrialised countries, the Swedish experience suggests that the technical problems are tractable. Thus, assuming informational, financial, and (perhaps most importantly) contractual barriers can be overcome, one might expect the fairly rapid diffusion to the six Asian NIEs of aqueous cleaning or `no-clean' alternatives to CFC-113 for surface mount applications.

In numerous instances, the need for customer consent was cited as a major factor inhibiting more widespread adoption of aqueous cleaning or other CFC-113 alternatives. As previously noted, many commercial electronics firms insist their contractors conform to `mil specs' as a reliability guarantee. While the US Department of Defense is overhauling its specs to allow for the use of CFC alternatives, this development is very recent. There appears to be an information diffusion lag regarding the acceptability of various alternatives. Moreover, those alternatives that have been qualified thus far are relatively high cost, notably HCFCs and semi-aqueous cleaning. There are also transaction costs involved in renegotiating contracts with customers to allow for alternative cleaning agents/processes. All these factors seem to have slowed diffusion.

Until recently, one contract assembler with a plant in Thailand did high volume assembly of high frequency TV tuners for a client, headquartered in a European country with a strict CFC phase-out schedule, who required the use of CFC-113 for cleaning. Since that customer's product accounted for the bulk of the assembler's solvent cleaning requirements, it was not willing to consider aqueous or other costly alternatives for its smaller customers until the major one agreed to a switch. (The contract has since been transferred to an Indonesian firm.) This is by no means an isolated example. Another large contract board assembler based in Thailand indicated that the biggest hurdle to more widespread adoption of aqueous cleaning would be convincing its customers to agree to the process change. For new customers, if CFC-113 is not explicitly required, it automatically opts for aqueous cleaning.

Not all firms in the Asian NIEs have been content to accept customer specifications at face value. In a few instances at least, firms have succeeded in gaining customer acceptance of the introduction of aqueous cleaning or a `no-clean' process. In one example, a PCBA contractor with plants in Singapore and Hong Kong is assembling a variety of products, including a double-sided surface mount board used in a blood sugar analyser marketed by a European medical electronics firm. The contractor spent some time getting the customer to qualify a new `no-clean' process using a low-solid solder paste. Finally, now that it has succeeded, it is hoping that the initial acceptance of the process by a reputable international firm will make it easier to convince other customers to agree to the process change. Another example is discussed in Box 2.

Box 2: Introducing "No Clean" for Video Display Boards in Taiwan

The Taiwan subsidiary of a leading US computer maker is building low-end computer terminals which are highly price competitive. Prodded initially by the parent company to reduce CFC usage, the subsidiary has used this as an occasion to cut production costs as well. Early on, it phased in an aqueous cleaning system with specially designed spray nozzles for cleaning its PCBs after wave soldering. Still, some water-sensitive components which had to be hand-assembled and soldered after aqueous cleaning were then cleaned with CFC-113. The company decided to eliminate this cleaning after hand soldering by moving to a low-solid flux. This required the approval of the corporate headquarters in the United States, which sets overall company product standards. After considerable testing, the Taiwanese subsidiary was able to convince the parent to rewrite the specifications for its video products to permit use of a no-clean process. Since the boards contain a small amount of flux residue which changes their appearance, it was necessary to revise the specs to allow for a slight cosmetic change in the event a no-clean process is used. Also, a clause was inserted stating that use of no-clean flux cored wire solder is acceptable as long as the board meets the original performance specifications and otherwise not. The maximum level of permissible ionic contamination was also raised slightly. It should be noted, however, that even the original standard (in terms of micrograms of sodium chloride per square inch) was considerably higher than the normal specifications for high-performance boards contracted out for assembly in the region.

The change in the process to eliminate one cleaning stage made it necessary to redesign the test fixtures, since cored wire solders contain plasticisers which, if not removed from the boards after soldering, inhibit testing with a `bed-of-nails' tester. Thus, at the contact points with those components which are hand soldered, the test probes had to be redesigned with three pins or with a single rotating pin to penetrate the residue and make electrical contact. Other subsidiaries of the company have approached the Taiwan subsidiary for advice on introducing a similar no-clean process. The subsidiary would apparently like the parent company to extend the the revised specs to include other than video products. De facto it has already agreed, since the subsidiary is also making printer products in the same plant using the same process. By eliminating one cleaning step, the subsidiary was able to reduce processing time as well as associated material, equipment, labour, space and other costs.

Cathode ray tubes (CRTs) for computers/TVs

Two firms manufacturing cathode ray tubes (CRTs) were visited in the course of the field research: a Taiwanese firm making CRTs for computer monitors and a Thai firm making CRTs for colour TVs. The former is a sizeable CFC-113 user, consuming roughly 6 tonnes a month (or 72 tonnes a year). The main application is in the cleaning of the shadow mask, a metal mesh that fits inside the glass bulb. Rather than CFC-113, the latter uses 1,1,1 - trichloroethylene (TCE) (approximately 30 tonnes a year) for washing the shadow masks.[14] The reason for the difference may have to do with the end uses of the firms' tubes. Due to the higher resolution required, the shadow mask for a computer monitor contains finer mesh than one for a colour TV; contamination is therefore more difficult to clean from the `pores.' The Taiwanese firm is setting up a CRT plant in Malaysia that would produce tubes for colour TVs and intends to dispense altogether with the cleaning of the shadow masks at that facility. In the Thai firm, the main operations using CFC-113 are the washing of the metal parts for the electron guns and the rework (i.e., cleaning) of the metal tips of defective tubes after testing. This post-test cleaning permits almost all defective tubes to be salvaged, though it would obviously be preferable to correct whatever flaw in the process gives rise to such defective parts. The quantities involved are considerably smaller than in shadow mask washing.

The Taiwanese firm has recently opened a new CRT plant with four production lines, each turning out 100,000 CRTs a month. It has converted one line from solvent cleaning to aqueous cleaning (using de-ionized water) on a trial basis. The capital investment in the aqueous cleaning system, which includes an ultrasonic generator, was around $150,000. As of January 1991, when the plant was visited, the new line had been in use for only three months but preliminary results seemed favourable: only a 1-2 per cent reduction in the yield compared to the CFC-113-based cleaning system. More recently, there have been discussions about introducing DI water cleaning on a second line, but a decision has not been made since a major change in machinery layout is apparently required. Still, the company has set a target to convert the other three lines to aqueous cleaning within 2-3 years. It has considered the economics of the process substitution and estimates that the switch over will reduce overall production costs (see next section).

The Thai firm, which is a joint venture between local and Japanese capital, has not been as actively exploring alternative cleaning processes. Still, it has adopted certain control measures. Its CFC-113 degreaser contains a solvent recovery system, which is reported to capture 95 per cent of the evaporated solvent in the electron gun cleaning area. The work pieces are inserted in and removed from the solvent with an automatic hoist to optimise cleaning time and minimise drag out. There is no recycling of the CFC-113 used in the rework area. The company expects, however, that solvent cleaning may be replaced before long by an electrical etching process. In general, the Thai firm expects any new cleaning processes to be transferred by the Japanese joint venture partner who is also the major technology supplier. Since restrictions on CFC-113 use are already in force in Japan, the use of alternatives is reportedly more advanced at the Japanese firm's Kyoto CRT plant.

Precision metal parts for electronics and other equipment

The metalworking industry is also a significant user of CFC-113 for degreasing. A number of electronic systems contain electromechanical components or subassemblies with metal parts requiring cleaning at various stages of production. There are three major electronics-related components/subassemblies discussed in this study whose cleaning has traditionally consumed large quantities of CFC-113: metal semiconductor lead frames (discussed above), computer hard disk drive (HDD) components, and miniature ball bearings for use in precision electro-mechanical equipment. In the case of HDD manufacturers, CFC-113 is used not only to clean metal parts like magnetic head assemblies but also printed circuit boards (PCBs) that go into their drives.

Collectively, manufacturers of hard disk drives and HDD components are among the largest users of CFC-113 in both Singapore and Thailand. Individually, the largest CFC-113 user in Singapore and the second largest in Thailand is an HDD manufacturer. Singapore has the largest HDD manufacturing capacity in the world. This accounts in no small measure for its large per capita CFC consumption prior to accession to the MP. By the same token, a significant share of the reduction in CFC use over the last few years has occurred within the HDD manufacturing sector. One large disk drive manufacturer in Singapore was a pioneer in the use of aqueous cleaning, having introduced the process about 2 years ago. Another, noted for high performance drives, is also reported to have adopted aqueous cleaning, suggesting that it does not pose insurmountable technical problems (an observation borne out by the IBM San José example cited above). Other HDD makers have also begun to switch to aqueous cleaning, but in most cases have only been using the process for a year or less. A few have encountered problems with water damage to critical components and, in one case at least, a large HDD firm has temporarily reverted back to CFC cleaning for some parts.

Observing CFC use by HDD makers in Singapore alone would provide an incomplete picture however, since most of the leading manufacturers now have two or more plants distributed around the region. Rising labour costs in Singapore have been a major factor contributing to a shift in production capacity to Malaysia and Thailand. It is not known to what extent reduced CFC use by firms' Singapore operations is compensated by increased use in Malaysia and Thailand; there may be some redistribution of consumption occurring within the region. Still, there is also evidence to suggests that some firms have managed to lower CFC-113 consumption both in their Singapore plants and in their operations in neighbouring countries. For example, one large US-headquartered HDD manufacturer with plants in Singapore, Thailand, and Malaysia was able to reduce CFC-113 consumption at its Penang facility by roughly 60 per cent in the first eight months of 1990 (even then consumption stood at 10 tonnes per month); on a per unit basis, CFC-113 consumption fell from 0.19 kg. per gimbal head assembly (GHA) in the second quarter of 1990 to 0.06 kg. per GHA in November 1990. The Penang plant is being requested by US headquarters to make additional process modification to cut use further. Among the measures adopted so far are the installation of mylar covers on degreasers, improved work and handling procedures, tighter stock control, and increased machine monitoring. There is also an in-house recycling programme, with stills built into degreasers. A major inducement to substituting for CFC-113 has come from the HDD maker's largest customer, a leading international computer firm which has encouraged its suppliers to eliminate CFC use. There has been no large-scale shift yet at this facility to aqueous cleaning, but the process is under examination and, assuming technical problems can be solved and the firm's financial condition permits, it is likely to be adopted in the near future.

Another US-headquartered firm makes high-performance disk drives for mainframes and minicomputers at production facilities in Singapore and Thailand. The Thai facility is a feeder plant which makes head stack assemblies for final assembly and testing in Singapore. Both facilities currently use CFC-113. The Thai plant has three batch-type degreasers, each with its own distillation column. Components are hand loaded in specially designed baskets which are immersed in and withdrawn from the vapour bath with automatic hoists. The Thai facility has achieved some CFC-113 savings, among others by using isopropanol (IPA) at certain work stations, though this apparently leaves stains on some metal parts. It is considering the purchase of a semi-aqueous cleaning system using a hydrocarbon-based solvent and has sent parts to the equipment vendor for evaluation. One concern — given evidently cramped quarters and skyrocketing real estate values in Bangkok — is the larger `footprint' (required floor space) of a semi-aqueous system versus a CFC degreaser. Reportedly, the Singapore plant is currently evaluating an aqueous cleaning process. Both subsidiaries are under pressure from headquarters to reduce CFC-113 consumption.

Finally, the leading user of CFC-113 in Thailand makes miniature ball bearings and other mechanical components for electronic equipment, especially computer peripherals. The parent company is a leading international ball bearing manufacturer, and Thailand represents its largest manufacturing base. The principal use of CFC-113 is in the removal of metal scrap particles after cutting and turning of the inner and outer rings which house the precision bearings, which are used in spindle motors for HDDs and in cylindrical motors for miniature video cameras. The metal balls are also washed with CFC-113. Solvent washing occurs again after assembly and before greasing. The firm also uses large quantities of MC to clean the larger bearing assemblies (from 13-30 mm. outer diameter).

Presently the company has no major programme to substitute for CFC and MC use. It does, however, follow certain control procedures. Recycling systems are built into the vapour degreasers, with a recovery rate of 65-70 per cent. The in-line degreasers have solvent piped in from beneath for automatic `topping up'; a leak in the piping was recently detected and repaired, reducing CFC-113 consumption by almost one-fourth. The company has been approached by vendors of alternative cleaning systems; for example, a German firm tried to sell a detergent-based cleaner, but the bearing maker was concerned that moisture remaining would oxidise the bearings. It is searching for a water repellant chemical or a system that would ensure thorough post-rinse drying. Its sister plant in Karuisawa, Japan, which also manufactures ball bearings, has reportedly been using aqueous cleaning for 2 years, but no information was available about its effectiveness. A Singapore affiliate has also switched to jet washing, using a mixture of water and TCE. The Thai operation has requested the Japanese headquarters to study alternatives that would be suitable for Thailand and is awaiting technical guidance.

Engineering plastics for use in electronics equipment

Many electronics products have casings made of durable and resilient engineering plastics. In many cases the plastic casing has a coarse, dull surface; in some however, the surface is smooth and must have a sheen (e.g., many telephone sets). Since CFC-113 cleaning results in a shiny finish and the solvent does not damage polymers, it has been used by telephone equipment makers to polish and coat the plastic during final set assembly. One large international telephone manufacturer with production in Singapore and Thailand discovered that isopropanol (IPA) could be used just as effectively for polishing casings. A firm in Malaysia making 7-segment displays for electronic instruments used to clean the plastic casings which house the displays with CFC-113. Then, it substituted a liquid organic cleaner—an off-the-shelf detergent reportedly bought from a household products distributor — which it now uses to wash the parts in an ordinary washing machine.

IV. BENEFITS AND COSTS OF CFC-113/MC SUBSTITUTION

Few detailed cost analyses of chlorinated solvent cleaning and its various alternatives have been carried out by the firms visited. Still, a rough cost-benefit picture can be pieced together from studies done elsewhere as well as from the cost information cleaned from the firm interviews for this study.

First, it is important to remember that for the majority of firms solvent cleaning costs represent a very small portion of total production costs (conservatively, less than 2 per cent and more often less than 1 per cent, before recent CFC price increases). In at least some of the Asian NIEs CFC-113 prices have risen steeply, so CFC solvent cleaning weighs more heavily in total costs than it did a few years ago. That trend can be expected to accelerate in the future. A number of firms, especially in Singapore, Hong Kong and Taiwan, have expressed concern about the high and rising price of CFC-113. While MC remains relatively cheap, that should also change now that it is included in the revised MP. Moreover, the US CFC tax, which applies to products containing or made with CFCs as well as to the chemicals themselves, has clearly been a strong cost incentive to finding alternatives. A number of firms mentioned that they must now report their CFC usage on shipments to the US market for tax purposes. All six Asian NIEs are heavily export-oriented and their electronics exports are highly price competitive. Thus, even cost savings of a few per centage points can be significant from their vantage point.

One detailed cost comparison of CFC-113 cleaning and aqueous cleaning carried out for the UK industry[15] estimates the cleaning cost per printed circuit board at 7.3 pence using CFC-113; with aqueous cleaning the cost per board rises to 13.8 pence. It should be noted, however, that this is based on UK labour rates, with labour costs amounting to 4 pence per board. It also assumes the use (and cost) of a surfactant/detergent. Waste water treatment/disposal costs will also affect total cleaning costs. Since effluent standards are stricter in the UK than in many developing countries, we might expect treatment costs to be higher as well.

A similar costing done in the United States has generated very different results. The costs of aqueous cleaning are estimated at $0.077 per square foot of PCB and those of CFC-113 cleaning at $0.228 per square foot (assuming US material, energy and other costs). A semi-aqueous, terpene-based cleaning process costs $0.165 per square foot. The high CFC-113 price used for the cost calculations is clearly the dominant factor, accounting for $0.178 (or 78 per cent) of the unit cost for the CFC-113 cleaning option.[16] Moreover, it appears that the US cost calculations include only recurrent and not fixed costs.

In the case of aqueous and semi-aqueous cleaning, capital costs are almost certainly significantly higher than with CFC-113 cleaning, especially since most firms will need to invest in a waste water treatment facility in addition to the basic cleaning system. (Waste treatment costs are especially high in the case of systems which use water mixed with an alkaline saponifier.) At the same time, aqueous cleaning (though not semi-aqueous) makes possible significant savings on material costs while semi-aqueous, terpene cleaning appears to reduce energy costs relative to CFC-113 cleaning. There is probably a slight net increase in energy requirements with aqueous cleaning, considering the need for ultrasonics and drying equipment. Of course, water bills can be expected to increase with both aqueous and semi-aqueous systems, but subsidised water charges in many countries limit this impact. On net, even with these cost increases, the evidence points to potentially sizeable cost savings per unit of output with the switch to aqueous cleaning, depending on CFC-113 price and scale of operation. The case for cost savings with semi-aqueous cleaning is less clear-cut and would seem to depend more critically on scale factors, given higher initial capital investments.

Perhaps the most detailed costing by one of the firms interviewed was that carried out by the CRT manufacturer in Taiwan. The relevant comparison in this case is between an aqueous cleaning system and an in-line vapour degreaser. The capital investment required for the degreaser is only 70 per cent of that required for the aqueous cleaning system. Still, the cost of one aqueous cleaner is only one per cent of the total capital investment in the CRT facility. The aqueous cleaner occupies a floor space almost 2.5 times larger than that of the CFC-113 degreaser. For firms operating in locations with especially high property values this may pose a problem. Energy consumption is slightly higher with the aqueous cleaner than with the CFC-113 degreaser. While both use an ultrasonic generator, the former requires a hot air dryer which is also energy-intensive and is the major additional energy cost item. The major cost saving is on CFC-113, which as previously noted the firm consumes in large quantities.

One medium sized firm in Thailand has estimated that, with a purchase price for an aqueous cleaning machine of roughly $200,000 and given the current price of CFC-113, three years would be required to recover its investment (even considering it already has a DI water treatment plant). For firms which must add on the latter investment, the payback period would be longer. The same firm has made another investment, in a small, year-old off-line CFC-113 recycling system, which costs around $20,000 and achieves a recovery rate of 70-80 per cent. The combined use of the aqueous cleaning system for some product lines and solvent recycling for others results in a monthly CFC cost saving of around $6,700, or a yearly saving of $80,400 (on an annual turnover estimated at $22 million in 1990).

There seems to be a widespread perception in the industries of the Asian NIEs that a `state-of-the-art' aqueous cleaning system (which generally means a US or Japanese one) requires too large a fixed investment for the average small electronics firm. Yet, not all the adopters of aqueous cleaning have been large firms, and not all the systems on the market are equally expensive. One Taiwanese firm which has switched to aqueous cleaning has annual turnover of only $10 million a year, from assembling printed circuit boards for facsimile machines and telephones. The company has realised a 50 per cent reduction in labour in its cleaning operations as a result of the switch. Energy consumption is estimated to have remained roughly the same. While the water-soluble flux is more expensive than the normal rosin flux, the reduction in CFC-113 consumption has resulted in a net material cost saving of around $1,100 per month, or $13,200 per year. Clearly, a medium-sized firm (by local industry standards) can justify investment at least in a locally made aqueous cleaning system (which is several times cheaper than a foreign-made one). In Hong Kong for example, a local company is making automated aqueous cleaning systems with ultrasonic generators which sell for approximately HK$300,000 (roughly $40,000).

There have been other cost savings specific to individual firms and their unique approaches to CFC reduction. A few examples were cited above of firms which have eliminated certain cleaning steps altogether without compromising product quality. In such cases the savings not only in CFCs but in labour, energy and equipment costs and processing time are obvious. Almost without exception however, the reduction in CFC purchases is expected to be the major source of cost savings to firms as CFC prices rise. Even if firms should opt for alternative solvents, they could reap savings in the medium term since the price of CFC-113 is expected to overtake prices of currently expensive substitutes like HCFCs sometime in the mid- to late-1990s. (Of course, depending on how quickly production of these transitional substances expands and that of CFCs contracts, the cross-over could occur even sooner.) In the case where firms opt for aqueous cleaning, they can look forward not only to solvent savings but perhaps also to reduced equipment costs as more models enter the market, fostering greater competition, and as individual suppliers reap learning economies, offering improved price/performance ratios on second- and third-generation machines.

V. LESSONS FROM THE ASIAN NIEs FOR OTHER DEVELOPING COUNTRIES

A number of conclusions follow from the preceding discussion which may be of relevance to other developing country Parties to the Montreal Protocol. First, from sections II and III, it is clear that countries which put in place a quantitative restrictions on CFCs send a clear signal to user firms to begin conserving on CFC usage. Initial reductions can be quite dramatic as firms which had few prior incentives to use CFC-113 sparingly begin introducing better housekeeping measures and engineering controls. In-house recycling also begins to look economical as virgin CFC-113 prices rise. The reductions achieved in this manner come at small marginal cost and, indeed, very soon generate net benefits. This would seem to provide a strong case for early implementation of control measures even in many Article 5 countries which technically enjoy a 10-year grace period. Incremental costs only begin to rise steeply, at least in solvent cleaning, once the phase-out has exhausted all the conservation, recycling, and low-cost substitution possibilities. Those combined, however, could well reduce CFC consumption by over half. An added consideration is that, if anything, the phase-out schedule is likely to be accelerated (and the grace-period possibly shortened) in the near future, which suggests that countries which start reductions early may be able to ease the adjustment process.

Where CFC costs have risen most and incentives for substitution therefore been the strongest, firms have been actively exploring longer-term alternatives. Transitional substances (e.g., HCFCs) have so far played a very minor role as CFC-113/MC alternatives. These have taken longer to become commercially available than anticipated and many user firms were not willing to wait. By far the most widely chosen options have been other alternative (largely alcohol-based) solvents or some form of aqueous cleaning. Aqueous cleaning has been more widely adopted than semi-aqueous cleaning, partly because of greater equipment availability and partly because of lower equipment and operating costs. There remain certain technical problems in specific aqueous cleaning applications but these do not seem insurmountable. In the case of PCBAs, as of early 1991 many firms were still hampered by the limited availability of suitable water soluble solder pastes for use in surface mount assembly. For this reason, many who had switched to aqueous cleaning of through-hole assemblies were still using CFC-113 for SM boards.

For smaller firms, limited production capacity is a concern in calculating the payback on investment in an aqueous cleaning system (and moreso in a semi-aqueous system). Small firms are reluctant to risk disrupting their entire process by wholesale conversion to aqueous or semi-aqueous cleaning; unlike larger firms, they do not enjoy the luxury of adopting a piecemeal approach.

Customer consent remains probably the single most important barrier to more rapid phase-in of CFC alternatives. Until customers have had enough time to evaluate alternative cleaning products and processes, Asian suppliers remain constrained in their own efforts to phase out CFC use. Independent assembly subcontractors face this problem most acutely, since they are largely bound to conform to customer-dictated specifications and, should they fail to comply, they may lose business to more compliant competitors. Arguably, an original equipment manufacturer (OEM) can exercise somewhat greater discretion in the choice of cleaning method, since the customer's costs of switching to another supplier are apt to be higher than in the case of a contract assembly house. This is due to the fact that the OEM generally possesses greater technical and managerial competence than a contract assembler. The relationship with customers therefore tends to be more durable (and more equal). To be able not only to evaluate an alternative process but to convince one's customer to accept the evaluation results presupposes a degree of technical sophistication which is lacking in many assembly subcontractors, especially new entrants with limited experience (which are commonplace in Thailand for example). Where assembly contractors lack the technical competence and/or resources to evaluate new cleaning processes on their own, major customers should be able to provide technical and perhaps financial support to assist in this process. While it may not be immediately apparent what incentive customers would have to provide such support, if the US CFC tax were levied on the CFCs used by those firms' offshore assembly subcontractors, that might provide just the right incentive.

The experience of the Asian NIEs suggests that there is considerable innovative potential within electronics firms based in the region. Faced with the need to respond urgently to a global environmental problem, and provided with right set of incentives, they have exhibited considerable ingenuity in devising alternative cleaning methods. Beyond their regulatory function, a number of governments have played a positive role in diffusing technical and market information to CFC users; in some cases they have provided centralised recycling services and helped firms evaluate alternative cleaning products and processes. Of course, even among the six, some countries have more highly developed technological capabilities than others, both in the public and in the private sector. Compared with the majority of developing countries, all six are more favourably positioned to shoulder the technical and financial demands of reducing their CFC dependence. Still, their example can serve as encouragement to others, and they have undoubtedly valuable experience and technical know how to be shared with their developing country neighbours who confront the challenge of meeting their commitments to help save the ozone layer.

NOTES AND REFERENCES

1. See "Evidence of Ozone Layer Depletion Over UK Confirmed," Department of the Environment News Release No. 447, 18 July 1991.

2. The ODP is a measure of the calculated ozone depletion potential of a compound relative to that of CFC-11, which is defined to have ODP = 1.0.

3. For more detailed descriptions of each of the six NIEs' CFC control strategies and policy frameworks, see D.C. O'Connor, 1991, *Strategies, Policies and Practices for the Reduction of CFC Usage in the Electronics Industries of Developing Asia*, Research Document, OECD Development Centre, Paris, June.

4. Faye Flam, 1990, "The Pace to Replace CFCs Quickens," *Chemicalweek*, Vol. 147, No. 25, 19-26 December: 51-52.

5. Quoted in Andrew Pollack, "U.S. Electronics Firms: Ozone-Friendly," *The International Herald Tribune*, 16 May 1991.

6. See UNEP, 1989, *Electronics, Degreasing and Dry Cleaning Solvents: Technical Options Report*, Nairobi, June 30, for more details.

7. The field research for this study was conducted between 25 December 1990 and 29 January 1991 in six Asian countries — Malaysia, Singapore, Hong Kong, Taiwan, Korea, and Thailand, in that order. A few additional interviews and factory visits took place in Thailand in April 1991. Altogether, roughly 30 electronics firms were surveyed in the six countries. Interviews were also held with government policy makers and scientific researchers studying CFC abatement or alternative technologies.

8. See USEPA, 1990, *Conservation and Recycling Practices for CFC-113 and Methyl Chloroform*, Peer Review Document, Washington, D.C., November, for more details.

9. See C.T. Kong, G. Tan, T. Yeoh, and C.K. Kong, 1989, *Montreal Protocol Economic Impact Analysis on Singapore*, prepared for the Economic Development Board, Singapore.

10. See J. Shandle, 1991, "Cutting Out Cleaning," *Electronics*, January.

11. This list of approved alternative cleaning agents to CFC-113 is contained in a recent letter from David W. Bergman, Director of Technical Programs of the Institute for Interconnecting and Packaging Electronic Circuits (IPC), to "All Members Department of Defense — Military Electronics Technology Advisory Group (DOD/METAG)".

12. Survey results reported by Dr. Johnsee Lee of Union Chemical Laboratories/Industrial Technology Research Institute in Taiwan at 1991

International Symposium on CFC, held at Taipei, 22-23 May, 1991.

13. This point is explained in the article by Jariyah Hashim of AMD (Malaysia), cited in Box 1 above.

14. As far as could be determined the chemical used for this process was 1,1,1-trichloroethylene (TCE) rather than 1,1,1-trichloroethane (methyl chloroform)

15. See Department of Trade and Industry (DTI), 1990, *Chlorinated Solvent Cleaning: The Impact of Environmental and Regulatory Controls*, A Report Prepared by Coopers and Lybrand Deloitte, London.

16. These cost estimates are taken from Case Study #1 of US EPA, 1991, *Aqueous and Semi-Aqueous Alternatives for CFC-113 and Methyl Chloroform Cleaning of Printed Circuit Board Assemblies*, Washington, DC, June.