行政院國家科學委員會精密儀器發展中心

赴歐美考察眞空儀器技術

發展及科技人才訓練

出　國　報　告

服務機關：行政院國家科學委員會精密儀器發展中心
出國人：彭永龍　技術服務組組長
　　林哲明　製造組工程師

出國地點：美國、英國
出國日期：中華民國八十九年十一月二十六日~十二月七日

摘　要

鑑於現代化及跨世紀高科技之發展，關係著我國在國際科技上之競爭力，其根基之奠定均有賴高科技人才之培訓及眞空技術之發展來達成。本中心爲蒐集最新資料掌握國際科技發展之現況，選派技術服務組彭永龍組長與製造組林哲明工程師，於十一月二十六日至十二月七日前往美國芝加哥西北大學實驗室、科學研究中心 MRC(Material Research Center)及西北大學育成中心之先進蒸鍍技術組 ACTG (Advanced Coating Technology Group)訪問，該中心投資七億美金在切削刀具類鑽石膜蒸鍍上之研究，享有國際公認先進之 PVD，CVD 及熱蒸鍍研究技術。並獲得極寶貴之開放實驗室及育成技服經驗。並參訪波士頓工業區生產製造冷凍眞空幫浦之 Helix CTI-Cryogenics 公司及眞空專業製造廠 Varian 公司，參觀離子幫浦、渦輪分子幫浦生產製程，並赴英國著名劍橋大學工程系實驗室及訪問泰勒豪伯生(Taylor Hobson)儀器公司，參觀生產粗度儀、平坦度儀、眞圓度儀及超平坦表面之奈米檢測儀(Nanostep)等組裝檢測過程。相機邀請相關高科技人員前來開設訓練課程，並尋求技術合作之管道，以吸收其企業經營及研發之經驗，加強本中心及產業各界之發展能力。

目次

一、前言

為提升本中心研究水準並掌握國際相關科技之發展現況，筆者參訪美國芝加哥西北大學材料科學實驗室、西北大學育成中心及麻州波士頓科學工業區眞空幫浦儀器相關生產製造工廠，並赴英國劍橋大學瞭解工程系科學實驗室之最新研究計畫及科技人才訓練情形，相機邀請相關高科技人員前來中心授課，以加強本中心之儀器技術能力。並尋求技術合作之管道，以廣吸收其企業經營及研發之經驗，俾供本中心規劃研製、維修、訓練之參考。

二、目的

(一)訪察美國芝加哥西北大學實驗室研究人員，以瞭解國際眞空幫浦及精密量測儀器技術之現況與發展趨勢。

(二)參觀Helix CTI冷凍幫浦、Varian眞空幫浦儀器公司，藉此機會與從事眞空儀器設備公司之專家相互交流，瞭解幫浦之研發技術、訓練規劃、技術移轉等工作，以建立本中心精密儀器技術之整體規劃及高科技人才之技術訓練能力。

(三)拜訪英國劍橋大學教授，並參觀Taylor Hobson儀器公司，藉由參訪並宣傳本中心在眞空、光電及微機電之技術能力，以促進與國際研究機構之科技交流管道，尋求技術突破之道。

三、過程

行程表

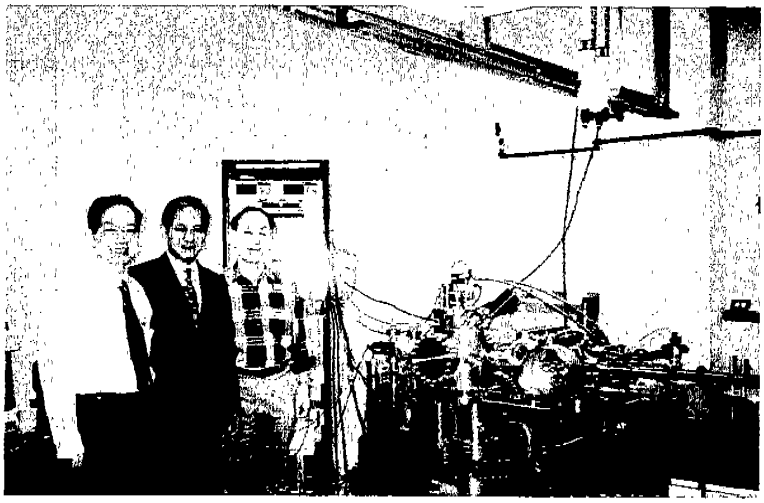
八十九年十一月廿六日～十二月七日共計十二天

日　　期	地　　點	工　作　內　容
十一月廿六日(日)	桃園→芝加哥	搭機/準備資料
十一月廿七日(一)	芝加哥	訪察芝加哥大學研究實驗室
十一月廿八日(二)	芝加哥	訪察芝加哥大學育成中心
十一月廿九日(三)	芝加哥→波士頓	搭機起程；安排住宿/準備資料
十一月卅日(四)	波士頓	參觀Helix CTI 冷凍真空幫浦公司、Varian公司
十二月一日(五)	波士頓→倫敦	搭機起程
十二月二日(六)	倫敦	安排住宿/準備資料
十二月三日(日)	倫敦	安排住宿/準備資料
十二月四日(一)	倫敦→Leicester→倫敦	參觀Taylor Hobson儀器公司
十二月五日(二)	倫敦	準備資料
十二月六日(三)	倫敦→桃園	搭機返國
十二月七日(四)	倫敦→桃園	搭機返國

(一)參訪美國西北大學材料系及ACTG育成中心考察

首程前往國科會駐芝加哥台北經濟文化辦事處科學組拜會張新雄組長和前中心同仁黃達明秘書，經科學組的安排引薦參訪美國西北大學材料系資深教授邱文安博士等人士（如照片 2-1、 2-2）。

(照片 3-1-1) 西北大學邱文安教授、與彭永龍組長、林哲明課長在辦公室外留影



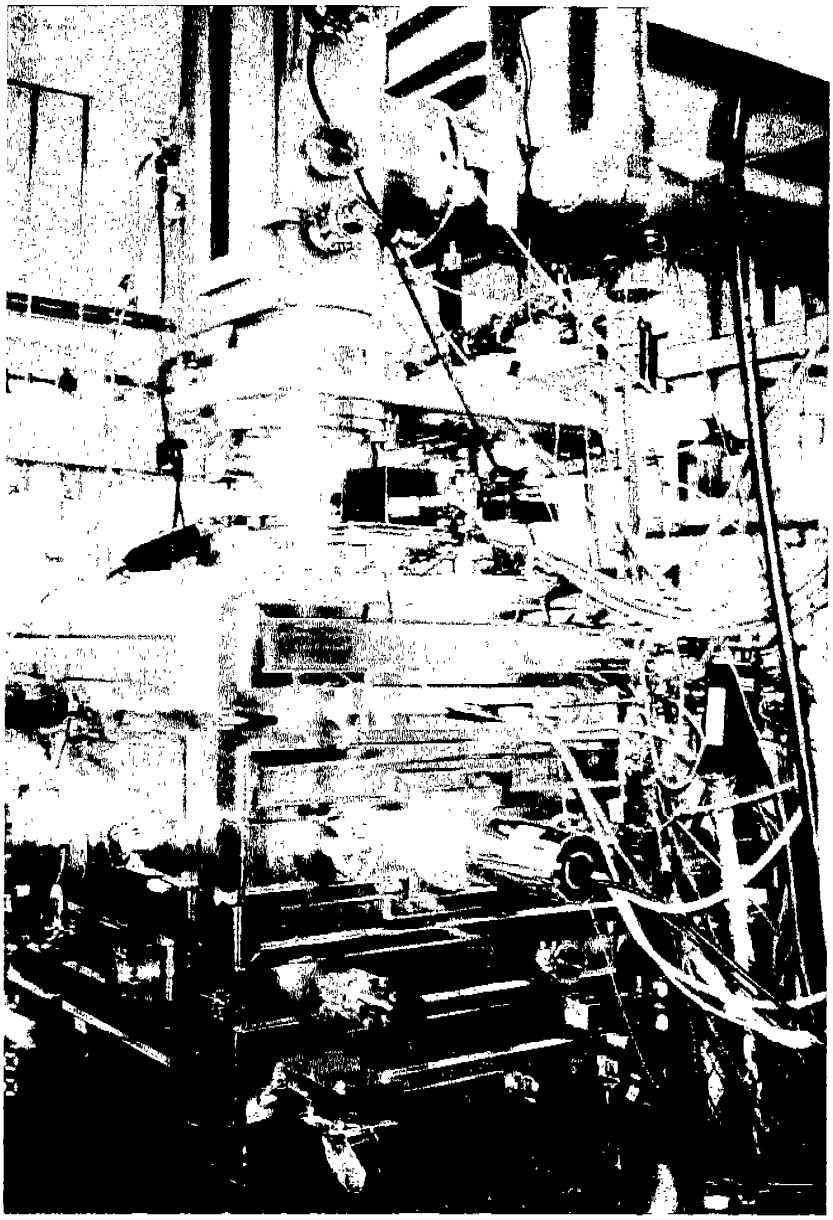
(照片 3-1-2)西北大學邱文安教授、與彭永龍組長、林哲明課長在實驗室留影

西北大學爲美國私立大學，創校於 1855 年至今已有 145 年之悠久歷史，該校在材料科學業界人才輩出，臺灣知名大學之材料系教授、新竹科學園區之半導體製程主管、工程師大都出自該校。西北大學目前有 7,400 位大學生，在 Evanston 校區有 4,300 位研究生，平面建築有 134 棟及 4 棟地下建築物，在芝加哥校區有 1,600 位研究生。1964 年西北大學藉由造鎮計畫，將密西根湖填土擴充了 85 英畝的環湖新生地，使該校土地規劃更加完美，從環繞密西根湖邊的校園去觀賞日出日落十分富有詩情畫意。

1992 年材料學工程系花費了三千九百萬美元新蓋「材料及生命科學館大樓」，這大樓有現代化的實驗室設施、會議室、學生中心等，由於設計規劃先進、考慮用途周詳實驗室空間可彈性擴充、應用寬廣，使研究員及師生們在運用上十分方便，研究實驗時技術更加精進。該系科學研究中心 MRC(Material Research Center)包括有基礎工業研究實驗室、觸媒及表面科學研究中心、品質工程及缺點防治中心、陶瓷科學研究、及國家科學高溫超導科技中心等。由於該系鑽研材料科學故其研究儀器設施十分齊備，重要之儀器設備有三部 VG 原子探針離子場顯微鏡(APFIM)、飛行式質譜儀、三台全套的 200KV 日立 HF-2000、H-700、H8100 場發射掃描穿透式電子顯微鏡(STEM)、一部高解析掃描式電子顯微鏡(High-Resolution Electron Microscope)、核磁共振儀(NMR)、原子力顯微鏡(AFM)、三五族分子束磊晶生長儀(MBE)、橢圓偏光儀(Ellipsometer)及數量繁多各式各樣之 X 光繞射儀等。依邱教授介紹說明西北大學材料系實驗室內之各種檢測儀器雖比台灣著名大學實驗室儀器舊一

一點，但研究生在好的實驗環境下，藉著教授之指導均能自行組合或改裝成實驗所需之設備。其中連早期的西門子(Siemens) X 光繞射儀，經更新電腦微軟視窗軟體後，操作起來並不輸給飛律浦新的產品。在電子顯微鏡的應用與推廣上，西北大學材料系尤其出名，電子顯微鏡的使用率十分頻繁，研究生經鑑定後均能上電子顯微鏡操作，並能維修保養，怪不得日本日立電子顯微鏡株式會社，都願意無償提供最新的電子顯微鏡給予使用。邱教授並陪同前往西北大學育成中心訪問，該中心投資七億美金在切削刀具類鑽石膜蒸鍍上之研究，並有先進蒸鍍技術組 ACTG(Advanced Coating Technology Group)，及被國際公認具有先進之 PVD，CVD 及熱塗佈研究技術，如(照片 3-1-3、4、5)，此次參訪探討獲得極寶貴之開放實驗室及育成技服經驗。

(照片 3-1-3)技服組彭永龍組長、林哲明課長在 ITEC 辦公室外留影



(照片 3-1-4)先進蒸鍍技術組(ACTG)之類鑽石真空鍍膜機設備

(照片 3-1-5)彭永龍組長、林哲明課長在 ITEC 聽取研究人員介紹 PVD 系統之架構。

(二)參訪 Helix 公司技術考察

接著轉往波士頓工業區生產製造冷凍真空幫浦的 Helix CTI-Cryogeni 公司參訪，該公司原爲美軍軍備供應的廠商，後來將冷凍的應用技術轉入生產半導體週邊之真空抽氣設備上，其中 ON BOARD CTI Torr-8、 Torr-10 冷凍真空幫浦爲其重要產品之一，年生產量三十萬台，在德州丹佛廠 Granville-Phillips,Helix Technology 公司爲專業製造真空計廠，其產品供應半導體、平面顯示器、讀寫磁頭及光電產品製造業，由於品質好、穩定性高、價格公道頗受真空業界採用。

Helix 公司全球支援部副總裁雷歐文(Ray Owen)、技術部經理 Steven C.Quagliozzi 向我們簡報稱：CTI 冷凍真空幫浦所有零組件之製造，除電路板由加州廠生產外其餘

均生產於此。CTI 冷凍眞空幫浦由於眞空抽氣性能十分良好，在半導體的 IC 製程設備機台(如台灣應材之金屬眞空濺鍍機、Varian、Eton 離子佈植機‥等)都採用該公司的產品。冷凍眞空邦浦(cryo-pump)的優點係利用一極低溫的環境，來吸附容器被排放的氣體分子，以達到抽氣(Pumping)的效果，這是一種超高眞空邦浦，其工作壓力約在 10^{-4}～10^{-11} Torr 之間。冷凍邦浦因抽氣速率大，無油氣污染，不使用氟氯碳化物(CFC)、液態氮，其電力消耗低，可安裝冷凍邦浦在任意位置，而不影響其導通與抽氣速率，故新竹科學園區生產半導體 IC 之公司所購之各國製程設備機台眞空幫浦均爲該公司之產品。

CTI 冷凍眞空幫浦生產線的製程有條不紊，產品分類清楚，二樓無塵室爲 Class3000，分五個區作零組件生產及品管部門用，中間一區約五百坪爲冷凍眞空幫浦組裝生產線，線上八人一字排開，組裝開始由雛形之幫浦馬達連同眞空外套缸到法朗座，逐步安裝冷頭柱、鋁片、輻射屏蔽、溫控二極體、(15K、80K)冷凝器後，逐步完成產品。裝配人員共八位作得十分起勁，重的組件安裝由六個男生負責，感測溫度二極體(Silicon Diode)的線十分微細、精巧、脆弱由兩位女生安裝。完成後移送組裝冷凍壓縮機，一樓冷凍壓縮機測試廠約八百坪，裝滿帶測之冷凍壓縮機，其中一部冷凍壓縮機泡在水中作觀測漏氣之試驗尤其壯觀，據現場工作人稱冷凍壓縮機均外包 OEM，然後到此切除壓縮機上蓋從新換油再焊接。由於 IC 半導體產業景氣復甦，只見該公司裝配完成一部部組裝之成品，排列整齊等候出貨前最後之品管檢驗。Helix 公司呈現生氣蓬勃的氣象，該公司副總裁雷 歐文在參觀前見我們時就慷慨應允提供專業技術人員，協助本中心的眞空幫浦訓練班，作高科技人才訓練之技術指導工作。

(三) 參訪 Varian 公司技術考察

隔天轉往最老牌之眞空專業製造廠 Varian 公司參訪。Varian 公司在眞空業界眞可謂金字招牌，該公司之眞空系列產品由設計、製造到眞空應用於半導體生產機台等應用上樣樣齊全。其產品如 ConFlat Flange、VacIon Pump、Contra-Flow 氦氣測漏儀等數十項專利產品，到目前還佔有極大的眞空設備市場。二十年前中心研發組眞空研究室之技術及研發人員均由該公司代爲培訓出來的，本中心當時培訓之技術及研發人員，如今均分別任職新竹科學園區半導體公司之總經理、廠長、副廠長或製程、設備之經理等，Varian 公司對台灣半導體科技人才之貢獻既深且遠。

Varian 公司在麻州波士頓 Lexington 工廠所生產之重要眞空設備產品以渦卷式乾式眞空幫浦(TriScroll Dry Pumps)、直立式渦輪分子幫浦(Turbo-V Pumps)及大型油性噴射擴散幫浦(VHS Series Diffusion Pumps)，可攜帶式氦氣測漏儀、眞空抽氣系統(Vacuum Pumping Station)及螺紋乾式眞空幫浦(Dry Screw Pumps)爲次要產品。其中較值得一提的產品就是渦卷式乾式眞空幫浦，四年前筆者曾參訪過 Varian 公司，當時之渦卷式乾式眞空幫浦爲日製 Iwatw ISP 500 之產品，此次參訪令我大吃一驚，全部零組件從 Scroll Pumps 之底座，均由 Varian Lexington 廠由一塊一塊的鋁錠切削生產，機械加工廠的 NC 車床快速加工中，車製之零組件運至二樓組裝線使用。由於中心多年來已與 Varian 公司建立深厚之情感，故此次特蒙 Mr. Tami Dawe 及 Mr. Bill Foley 引薦 Mr.Dave Vincett 及 Mr.Ronald J.Stanton 兩位專家(如照片 3-3-1)，解說離子幫浦(Ion Pum)及渦輪分子幫浦之故障診斷及維修技術。

(照片 3-3-1)筆者與 Mr.Dave Vincett 及 Mr.Ronald J.Stanton 兩位專家研討離子幫浦及渦輪分子幫浦之故障診斷及維修技術

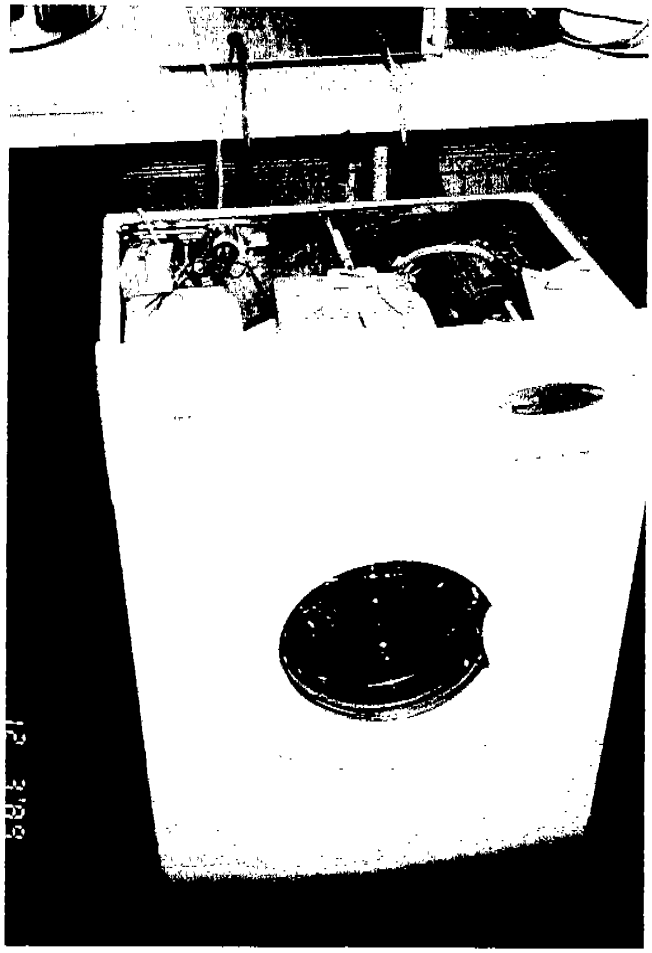
並贈與相關 VCD 保養資料及技術手冊，並提供一份真空技術訓練規劃課程，供本中心高科技人才技術訓練班之參考，獲益匪淺。

（四）參訪英國劍橋大學工程系考察

此行緊接著轉往下一站英國劍橋大學工程系，因中心同仁呂志誠先生考取公費留學就讀該校攻讀博士之便，參訪其研究所之工程系研究室。這時段雖爲該校放寒假期間，但實驗室還有許多學生留校作研究，在電子工程學系上有許多來自中國大陸之留學生，每個人都學有專精，有的專攻奈米材料、半導體感測元件或電力轉換技術等高科技學門。在工程系研究室設有 Class100 之半導體無塵室，及晶圓曝光黃光室、高倍率電子顯微鏡等檢測設備。中國留學生盛況先生爲劍橋大學博士後研究員，係十分傑出之科技人員，自大陸北京大學畢業後就到劍橋大學直攻博士三年就完成學業，目前爲博士後研究員。他暢談其研究專題計畫爲洗衣機電力之改善工程（如照片 3-4-1）

（照片 3-4-1）劍橋大學電子工程學系大陸留學生與筆者留影

，計畫經費由廠商提供含有高額獎助金得以生活無慮專注研究改進洗衣機旋轉之馬達爲高效率、低噪音、低耗電力之產品（如照片 3-4-2），從研究計畫中獲得專利技轉民間廠商，此種作法與國內創業育成中心十分相似。英國劍橋大學之儀器設備有點類似美國西北大學，均非新購之儀器設備，但由於保養得宜及用心使用又經最好之教授調教，故儀器均能淋漓盡致地發揮功用並發表最好的論文。



（照片 3-4-2）劍橋大學盛況博士研究改進洗衣機旋轉之馬達樣品

(五)參訪 Taylor Hobson 儀器公司技術考察

最後一站訪問泰勒、豪伯生(Taylor Hobson)儀器公司，由區域銷售負責技術主管Mr.Melvyn Chase帶訪參觀生產(TalySurf Series 2)粗度儀、平坦度儀、眞圓度儀及超平坦表面之奈米檢測儀(Nanostep)等組裝檢測過程並由非球面量測儀器系統，量測實驗室主管Mr.Pat Kilbane接待解說標準檢校實驗室之標準件儀器如何通過ISO 9001及UKAS之認證體系。由於本中心具有非球面光學鏡片研磨、奈米表面檢測技術及雷射微細處理系統技術能力，故在參訪時順便宣導本中心精密量測技術能力外，並接洽能與泰勒、豪伯生公司技術合作，以促進本中心與國際先進廠商之科技交流管道，使本中心在精密量測之研發、設計及製造上能同步並進。

四、心得

此次考察英、美國大學實驗室研究人員及儀器製造業者，透過雙方當面彼此研討洽談，加深雙方技術交流與合作之意願。茲將此次考察洽談心得，概述如下：

一、在參訪美國西北大學材料系實驗室時，邱教授直接了當的說，我們沒有像台灣有那麼多的錢買最新的儀器設備，你們在台灣實驗室的設備比我們的大學還要好、還要新。聽了這話，起初我還以為邱教授太謙虛了，但當我們參觀過後才發覺他們的儀器設備的確比國內舊一點，可是在儀器系統之整合及應用上卻比國內好了很多。西北大學的儀器設備功能發揮得很好，沒有系所霸佔的情形、由實驗室儀器使用記錄來看，使用率非常的頻繁，幾乎滿檔，連晚上都有研究生在使用。各式各樣舊的儀器設備，都經過教授帶研究生親自作整修，使其性能提高。學生在這種良好的教學氣氛下，亦能動手做儀器系統的拆卸分解與整合。這種作法無形中提升了研究生在研究計畫上的實力，在做完研究發表論文時有新的創作及發明的專利，所以西北大學材料系的論文在國際研討會發表時十分出色。

二、在參訪英國劍橋大學工程系實驗室時印證了上述的說法，英國這個國家不是比誰的房子最新，反而看重誰的房子歷史最久保養得最好。在倫敦市區或劍橋校園裡的建築物，到處可以看到牆上訂著牌子標出，這裡有位偉大的科學家 1885 年住在這棟房子裡他發現「原子」。

劍橋大學工程系的機械工廠裡皮帶傳動的車床還可以使用，電子工程系的儀器設備因為研究半導體及奈米計畫所以比較新，電腦均使用工作站。其他的研究計畫儀器設備都比國內舊一點。但研究生均能動手組合真空蒸鍍儀器系統作實驗。反觀國內研究生由於動手的機會很少，一方面缺少專家的指點，一方面無系統整合能力，

無法自行設計或組裝，只好依指導老師所提供國外的書籍，照書上所說的請外面的工廠設計、估價然後加工製作，研究生僅能將研究重點放在理論數據的模擬及運算中。

三、美國西北大學材料系之育成中心有先進蒸鍍技術組ACTG(Advanced Coating Technology Group)，其PVD、CVD及Thermal Spray的研究技術（如照片3-1-4）在推廣工業之應用上成效卓著，由於該育成中心採策略聯盟會員制，凡參加之會員均享有最新蒸鍍技術服務、專屬技術專家諮詢服務、特殊材料之提供、及送驗樣品優惠折扣(special Low Overhead Rate)及免費參加研討會等，由於經營得體獲利豐富，這種作法有點像清華大學工學院正在推動的『產學研合作聯盟』的作法，或許是英雄所見略同吧!

四、由於世界性景氣低迷百業蕭條，在訪察歐美期間聖誕節將近了，但百貨公司採購人潮卻沒有以往的洶湧，由此可以瞭解到各行各業的情形。因著IC半導體產業的復甦，若與半導體相關之儀器產業均欣欣向榮。由Helix、Varian、Taylor Hobson公司的需求量大增，完成大量儀器產品等候出貨檢驗，可見一斑。

五、檢討與建議

1.出國考察，固以汲取國際經驗、資訊爲主。然而如欲持續建立聯繫管道，適當宣導本單位的狀況，亦屬需要。因爲技術合作或交流必須奠定在雙方基本的技術能量條件之上。此次參訪西北大學邱教授等實驗室後，邱教授曾於下班後蒞臨下榻旅館晤談至凌晨一時，其因鑑於本中心眞空技術之獨特能量，而極欲與本中心進行合作研究，共同致力提昇電顯功能，顯示以本中心所累積的技術經驗及軟硬體設施，確實足以進行國際性世界級專業領域的合作交流。

2.科技專業人才培育，是躋身世界先進國家之林的首要途徑，爲汲取新知、拓展視野，在內外因素造成國人出國深造熱潮衰退的今日，邀聘國際知名學者專家來台擔任講座，將可舒緩負面效應產生，本中心職司科儀專業人才訓練，宜爲留意加強。

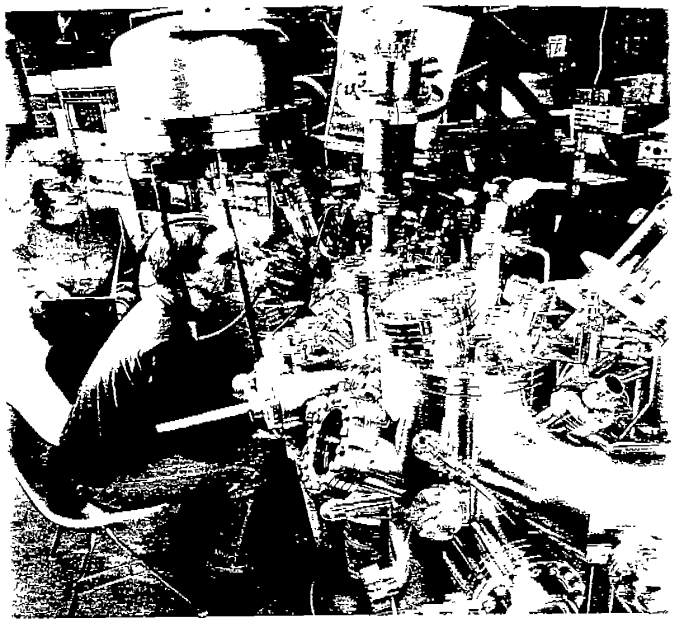
3.現代化科技研究，學科特色明顯，專業化差異很大，相對的，對於研究設施，尤其是對精密儀器的性能要求不同。在英、美固然民富國強，但是科技研究人員並不以擁有最新昂貴設備自詡，而以提昇創新原有設備之功能相期許，值得國人效法。

六、結語

本次出國考察美英著名大學及績優廠商。深切領會了其所以卓越的因素。在學校學術研究風氣盛行，資源也相當完善，尤其與工業界關係良好，如日本日立電顯株式會社跨國無償提供美國西北大學最新電顯從事實驗研究，劍橋大學爲數可觀的廠商委託研究，因此研究成果相當良好。至於各廠商對於產品研發創新的企圖心極爲強烈，大公司致力全球發展策略，小公司朝專精不可取代性發展。他山之石，可以攻錯。今後，將就所歷見聞，作爲日後執行業務之重要參据。

七、附件目錄(技術資料)

Some Background on Materials Science and Engineering at Northwestern



Northwestern University was a pioneer in recognizing the importance of studying the science and technology of all materials, not just metals. That awareness led to the first materials science academic department in the world. Our materials science department began in the 1950s when a group of faculty realized that the fields of metallurgy, ceramics, polymers, and electronic materials could be merged and studied as a whole.

Shortly thereafter Northwestern was chosen as one of three sites to house new federally funded materials research centers for collaborative work by materials scientists, physicists, and chemists. The Materials Research Center at Northwestern was able to establish state-of-the-art research facilities available to students as well as to professors and visiting scientists.

The graduate-level Department of Materials Science grew rapidly as faculty members were added to provide an integrated, broad approach to materials science. To reflect the developing strengths in engineering as well as science, "engineering" was added to the department name in the 1960s. In addition, an undergraduate program was established at about that time.

The department achieved and has maintained a world-class reputation, due to a large extent to the outstanding achievements of our faculty and graduate students in every area of materials research. As the founders of the department retire, the vigorous young professors who take their place continue our reputation for excellence. Six recently hired faculty members have won prestigious National Science Foundation Young Investigator Awards. Our reputation is due as well to our graduates' outstanding careers as educators, research scientists, corporate executives, and research and development engineers.

Today our department has 26 faculty members and some 120 graduate students and 60 undergraduate students.

Research opportunities have continued to expand as other science centers have been located at Northwestern. The two latest are the National Science Foundation's science and technology centers on high-temperature superconducting materials and on cementitious materials. In addition, the department's move into a new building in 1992 increased our research laboratory space

Since the department was organized, the interests of the faculty have spread broadly across the physical sciences and engineering. Materials science faculty collaborate extensively in research and teaching with colleagues in other departments. The other engineering departments as well as the physics and chemistry departments are housed in a building attached to ours, furthering collaboration.

Graduate students' working relationships with colleagues extend beyond departmental and even University boundaries. Our large number of industrial contacts and the newly established Crown Family Graduate Internship Program (see page 4) make it possible for graduate students to gain industrial experience while working toward their degrees.

Our department's mission today continues the farsighted and broad vision of its founders.

- To provide a well-rounded education in materials science and engineering to meet the needs of industry, academia, and government
- To give definition to the evolving discipline
- To conduct frontier research
- To provide leadership in the interdisciplinary materials community

Graduate Study

The department offers both MS and PhD degrees in materials science and engineering. Evaluation of applicants for either degree is based on the same criteria. The MS is not required for the PhD.

We strongly recommend that students begin their graduate programs in the fall quarter, although those with unusual circumstances and an appropriate background may begin in the winter quarter or during Summer Session.

The graduate program in materials science and engineering is designed to integrate core courses that apply across the field, specialty courses selected with the adviser, and research. Students have opportunities to develop presentation and writing skills through participation in individual research groups, presentations at national and international meetings, and submission of papers for publication. Students interested in teaching participate as full- or part-time teaching assistants in graduate and undergraduate courses.

PhD Program

The PhD curriculum includes seven courses that provide a foundation for any specialization within materials science and engineering. Students take eight additional courses, two of which constitute a recognizable minor. The other courses are appropriate to the specialization or are useful for dissertation research. The following list of courses is not inclusive because new courses based on emerging fields are continually being developed. For example, biomaterials was taught in 1994–95 as a special topics course.

Core Courses
- D-01 Chemical Thermodynamics of Materials
- D-02 Symmetry and Physical Properties of Materials
- D-03 Statistical Thermodynamics of Materials
- D-04 Imperfections in Materials
- D-05 Physics of Solids
- D-06 Deformation and Fracture
- D-07 Phase Transformations in Materials

General Courses
- C-22 Kinetics of Heterogeneous Reactions
- C-33 Composite Materials
- C-90 Materials Design
- D-11 Phase Transformations in Crystalline Materials
- D-12 Interfaces in Crystalline Solids
- D-32 Advanced Mechanical Behavior of Solids

Characterization Courses
- C-61 Crystallography and Diffraction
- C-80 Introduction to Surface Science and Spectroscopy
- C-85 Stereology
- D-60 Electron Microscopy
- D-61 Diffraction Methods in Materials Science
- D-65 Advanced Electron Microscopy and Diffraction
- D-66 Analytical Electron Microscopy

Ceramics Courses
- C-40 Ceramic Processing
- C-41 Introduction to Modern Ceramics
- D-40 Crystal Defects and Transport Phenomena in Ceramics
- D-41 Selected Topics in Ceramic Science

Electronic Materials Courses
- C-55 Electronic Materials
- C-98 Introduction to Plasma Science and Processing Technology
- D-15 Fundamentals of Thin Film Materials
- D-51 Advanced Physics of Materials
- D-52 Selected Topics in the Solid State

Metals Courses
- D-34 Fatigue and Fracture
- D-35 Special Topics in Mechanical Behavior of Solids
- D-64 Advanced Dislocation Theory

Polymers Courses
- C-31 Physical Properties of Polymers
- D-44 High Polymers in the Solid State
- D-45 Special Topics in High Polymer Science

A wide variety of courses in other science and engineering departments may be used for the minor or as electives.

In addition to course work, PhD candidates write and defend a research proposal before a committee of four people—three faculty members from the department and a fourth person from another department or from outside the University. The same committee reads the final dissertation and hears the student defend it.

Crown Family Graduate Internship Program

PhD candidates may choose to participate in the Crown Family Graduate Internship Program, gaining practical experience in industry or national research laboratories in areas related to research interests. An internship can significantly boost the thesis effort and may provide a basis for future employment.

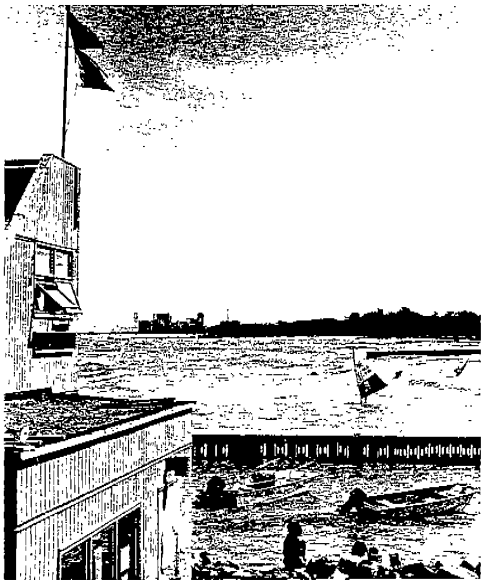
A student may elect the graduate internship option in the latter stages (e.g., third year) of PhD study. A proper position is found with the help of the student's PhD adviser and the associate deans of graduate studies and of research and industry/academic affairs. The student works full-time for three, six, or nine months and generally is paid by the participating sponsor. At present, U.S. citizenship is a requirement.

MS Program

Master of science candidates take eight courses, at least six of which are in the department. The latter include D-01 Chemical Thermodynamics of Materials and two other D-level courses. A wide variety of courses in other science and engineering departments may be used as electives. MS candidates write a thesis and defend it before a committee of three faculty members from the department. A paper accepted for publication may be substituted for a thesis.

Research

Each PhD and MS candidate works closely with a faculty adviser on a research project. Projects may be experimental, theoretical, or a combination, depending on student and faculty interest. Through faculty involvement in collaborative research and through the science and technology centers, research teams often include other Northwestern faculty members, professors from other universities, scientists from national laboratories (particularly nearby Argonne National Laboratories), postdoctoral research associates, and other graduate students. All research done in the department directly applies to the dissertation or thesis. We believe that active involvement in and reporting of original research are key elements in a graduate student's maturation.



Northwestern's lakefront campus in Evanston provides scenic beauty and recreational opportunities.

Graduate Life

Proximity to Chicago gives students access to world-class cultural and recreational resources.

Extracurricular Activities

The Department of Materials Science and Engineering sponsors many programs to broaden students' exposure and experience. Our colloquium series allows graduate students to hear and meet with leading researchers from around the world whose interests cover a wide range of topics. Leaders in the discipline are brought to the campus in annual distinguished lecture series sponsored by companies such as Dow, Armco, Shell, and Inland Steel. The department also sponsors the annual John Dorn Memorial Lecture, named in honor of one of our most prestigious alumni.

The Materials Science Student Association provides a forum for graduate students to interact with faculty informally and through a representative to faculty meetings. In addition, each spring senior graduate students present their research to scientists from academia and industry in the annual John E. Hilliard Symposium.

The student association organizes many social and professional activities. Professional events include trips, talks by invited speakers from industry, and seminars. The group attends local professional society meetings. After new student orientation, the association sponsors bimonthly happy hours, picnics, bowling nights, and culinary outings. It also enters competitive teams in intramural sports.

Another organization, HANDS (Haven and Northwestern Discover Science), gives graduate students the opportunity to be mentors to seventh and eighth graders from the local Haven Middle School.

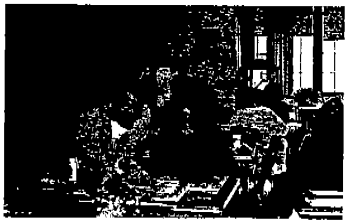
The Campus

A major private research university, Northwestern has 6,500 graduate students and 7,500 undergraduate students. On the Evanston campus, 12 miles north of downtown Chicago, are located undergraduate programs and the graduate programs in engineering, management, the arts and sciences, music, speech, education and social policy, and journalism.

Extracurricular resources on the Evanston campus include Big Ten sports events; performances by visiting artists as well as Northwestern's music, theater, and dance faculty and students; film showings; game rooms and gathering rooms in the student center; water sports and a private beach. The Henry Crown Sports Pavilion and Norris Aquatics Center houses an Olympic-sized swimming pool; a conditioning room; tennis, squash, and racquetball courts; and a jogging track. Surrounding the campus is the city of Evanston, with restaurants, a central business district, and a cosmopolitan population of 70,000.

The Metropolitan Area

By venturing a few miles to the south, students can savor the resources of one of the country's great cities. Chicago has something to offer every taste, including a world-renowned symphony, architecture, and museums; blues and jazz clubs; theaters; professional sports teams; ethnic neighborhoods; and restaurants of every type.



Middle-schoolers in a mentor program offered by graduate students investigate the materials science of the bicycle (left) and consider careers in science (right).

Facilities, Centers, and Other Resources for Research

The Department's New Facilities

In 1992 the Department of Materials Science and Engineering moved into a new Materials and Life Sciences Building. The building gives us much-needed room to expand while keeping us close to our colleagues.

The four-story, $39 million structure provides us with modernized laboratories, conference rooms, and offices. Collaboration and student-faculty interactions have been enhanced through integrated office-laboratory design. The building has state-of-the-art safety, energy-efficiency, and environmental impact systems.

A physical symbol of Northwestern's commitment to interdisciplinary research, the Materials and Life Sciences Building is connected by covered walkways to both the Technological Institute, home of the McCormick School's other engineering departments, and Hogan Hall, home of biological sciences.

Science Centers at Northwestern

These centers provide opportunities for research with professors from materials science and other Northwestern departments as well as with scientists from other institutions.

Materials Research Center
Part of the Materials Research Laboratory Program of the National Science Foundation, the MRC is responsible for 19 facilities with major research equipment for synthesizing and characterizing materials Current areas of research include electroactive polymers, heteroepitaxial strained layer structures, nonlinear optics, electronic and photonic metal oxide thin films, and unconventional superconductivity.

Basic Industry Research Laboratory
An applied research and development facility, BIRL works under contract to companies, research consortia, and government agencies. It offers an integrated approach to the materials, manufacturing, and environmental problems of basic industry.

Center for Catalysis and Surface Science
The center broadens the scientific and technological bases of catalysis and surface science. Faculty participants come from chemistry, chemical engineering, materials science, and physics. Center members, graduate students, and research associates attack significant problems such as the mechanism of Fischer-Tropsch synthesis and the design and characterization of catalysts not based on rare and expensive metals.

Center for Engineering Tribology
This center was established in 1984 under National Science Foundation sponsorship to promote interaction and technology transfer between university and industrial researchers. It performs basic and applied research in the science of friction, wear, lubrication, and adhesion and distills its knowledge into computer codes immediately useful to industry. The center has federal and corporate support.

Center for Quality Engineering and Failure Prevention
This center's research focuses on new technology and product quality, particularly prevention of premature failure. It integrates research and development in materials science, nondestructive evaluation, sensor development, expert systems, surface and interface science, computer-aided engineering, and the economics and management of innovation.

Science and Technology Center for Advanced Cement-Based Materials
This National Science Foundation science and technology center teams researchers from Northwestern, three other universities, and the National Institute of Standards and Technology. They are searching for stronger, lighter, less costly, and more energy-efficient cement-based materials for use in new construction and infrastructure repair.

Science and Technology Center for the Study of Superconductivity
Northwestern University is one of four partners (with the University of Illinois, Argonne National Laboratories, and the University of Chicago) in a Science and Technology Center for

The large building in the center of this campus panorama is the new Materials and Life Sciences Building, home to our department. It is next door to the Technological Institute, which houses our engineering colleagues in other departments.

the Study of Superconductivity funded by the National Science Foundation. The center carries out major research in high-temperature superconducting materials. Current theme areas are structural and compositional basis for superconductivity, implications of unusual normal-state properties for superconductivity, and vortex dynamics and critical currents. Ongoing research on superconducting thin films is also being carried out.

Research Facilities

Atom-Probe Field-Ion Microscopy

Atom-probe field-ion microscopes (APFIM) provide the ability to observe individual atoms directly and to determine their chemical identities via time-of-flight mass spectrometry. The phenomenon of field-evaporation permits atomic-scale chemical analyses in the three-dimensional direct lattice space of a wide range of materials.

There are three APFIMs at Northwestern. One is a commercial VG Instruments Ltd. FIM/100 with a Poschenrieder lens. The second APFIM is a straight time-of-flight instrument with features for performing in situ experiments such as low-energy (25-eV to 3-keV) ion irradiation, vapor deposition, and 20-keV electron irradiation. The third APFIM is a specially fabricated system with three interconnected spherical chambers. The main chamber is a high-mass resolution APFIM with a reflection lens. The second chamber allows different in situ treatments of FIM specimens—e.g., oxidation, multilayer superlattice formation via vapor deposition, low-energy ion irradiation, and electron or cluster irradiation. The third chamber is a tomographic atom probe that allows for the simultaneous determination of the position and the chemical identity of an atom. A specimen can be moved among these three chambers under ultrahigh-vacuum conditions.

Ceramics Facility

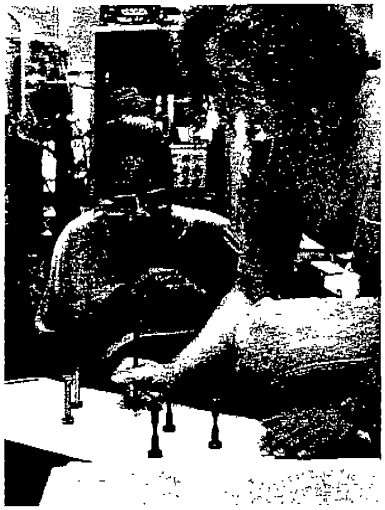
Students prepare, mill, and characterize ceramic powders and then fabricate them by pressing, isostatic pressing, slip casting, extrusion, hot pressing, and sinter forging. Equipment includes a hot isostatic press for firing at temperatures up to 2,300° C and an ultrasonic machine tool for drilling, planing, and milling ceramic particles.

Electronic and Photonic Materials Characterization Laboratory

This laboratory contains spectrophotometer systems for determining optical properties of materials, including photoluminescence, photoconductivity, and photocapacitance. A Fourier transform infrared system is available for high-resolution studies. A Hall Effect analyzer, an ECV profiler (for carrier concentration measurements), a curve tracer (for semiconductor device analysis), an impedance analyzer, and a spectrometer (for optical analysis) are also available.

Electron Probe Instrumentation Center

Various electron microscopes within the Materials and Life Sciences Building have been consolidated in the new Electron Probe Instrumentation Center (EPIC), making for one of the world's most complete arsenals of routine and state-of-the-art



electron microscopes. In addition to a complete specimen preparation facility, EPIC houses the following facilities for scanning electron microscopy (SEM), transmission electron microscopy (TEM), and scanning transmission electron microscopy (STEM):

- A fully equipped Hitachi HF-2000 atomic resolution analytical electron microscope, with a high-brightness cold-field emission gun operated at 200 kV. With its many analytical attachments and STEM, this microscope forms the centerpiece of the TEM section of EPIC.
- A Hitachi H700 200-kV transmission electron microscope, equipped with a STEM unit and a Tracor-Northern X-ray analyzer.
- A new Hitachi H8100 200-kV TEM with STEM capabilities, BF/ADF/microdiffraction detectors, and PC-based acquisition system.
- A state-of-the-art cold-field emission gun scanning electron microscope (Hitachi S4500-II) that offers unprecedented spatial resolution and analytical sensitivity, both at high (30-kV) and low (0.5-kV) voltages. It is equipped with energy-dispersive spectrometer (EDS), electron back-scattered Kikuchi pattern (EBSP), and liquid Helium stage.
- A Hitachi S570 conventional scanning electron microscope equipped with a Tracor-Northern X-ray analyzer and BSE imaging capabilities.

Two highly qualified microscopists manage the EPIC facilities, and regular training sessions and short courses are offered.

High-Resolution Electron Microscope Facility
This facility includes a high-resolution electron microscope (resolution better than 1.8 angstroms) that is fully interfaced with a set of computers for high-speed image analysis and interpretation. In addition, a unique multichamber system combining thin-film growth, chemical characterization, scanning electron microscopy, and UHV high-resolution electron microscopy is available. All chambers are part of single vacuum system operating under ultraclean conditions.

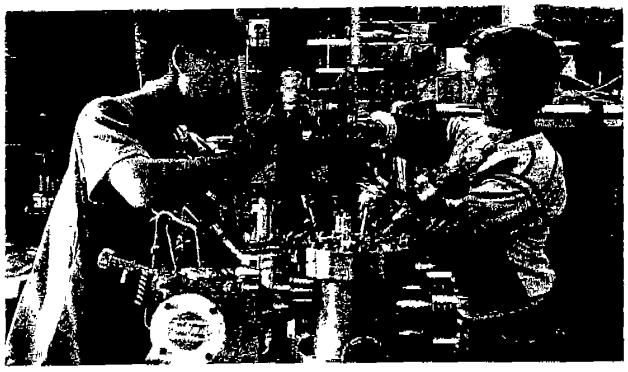
Materials Processing and Crystal Growth Facility
This facility offers equipment and expertise for producing metals, alloys, oxides, semiconductors, and other nonmetallic compounds in polycrystalline, single-crystal, or bicrystal form. Available techniques include Czochralski and floating zone methods, arc melting, vacuum casting, chemical vapor transport, and evaporation. These methods can be used in a vacuum or a variety of controlled atmospheres and allow selective doping of the materials.

Equipment is also available for zone refining, zone leveling, and vacuum filtration of medium melting-point materials. Levitation and cold crucible techniques are available for the preparation of highly reactive materials in inert gas or vacuum atmospheres.

The facility also houses the Electronic Materials Laboratory, with equipment for chemical vapor deposition and molecular beam epitaxy for growth of III-V semiconductor and oxide thin films and for epitaxial growth of metallic materials. The laboratory is in a class 100-to-1000 clean room and includes microlithography instrumentation, including a Quintel mask aligner, photoresist spinners, and reactive ion-etching capabilities.

Mechanical Properties/Fatigue Facility
MTS servohydraulic, servoelectric, and screw-driven machines are interfaced with computers for studying the mechanical behavior of materials. The machines operate in either a manual or computer-controlled mode for static or dynamic testing. They allow study of elasticity, plasticity, fatigue life, and/or fracture of materials. Real-time fatigue crack growth can be observed with a metallurgical microscope attached to the testing units. Temperature (4.2 K to 1373 K)-, environment-, and rate-dependent properties can be observed over a wide range of all parameters. A Sperry attenuation comparator and a pulse comparator are available for dynamic determination of the elastic properties and internal friction of solids. Constant load creep apparatus can be used for creep and stress rupture experiments.

Optical Microscopy and Metallography Facility
Equipment for preparing specimens for optical analysis includes diamond blade saws, polishing wheels, and 12 microscopes and metallographs using reflected and transmitted light with magnifications ranging from 6x through 1,600x. Selected microscopes



have Nomarski optics using polarized light. Two microhardness testers, an interference microscope, a hot-stage, and an image analyzer (programmable in Turbo Pascal) for microstructural analysis are available.

A furnace room holds two high-temperature box furnaces, one salt furnace, one low-temperature box furnace, and two high-temperature tube furnaces.

A digital darkroom has been established for electronic photo reproduction. Digital images can be captured directly from certain microscopes. Images are processed using state-of-the-art software and printed on a Codonics color printer. A scanner is available to digitize photographs for further image processing. A conventional darkroom is also available.

Polymer Characterization Facility
This facility houses equipment used primarily for polymer characterization. Molecular weights can be measured by light scattering or solution viscosity. Thermal behavior can be studied with a differential scanning calorimeter with thermogravimetric capabilities.

Other equipment includes density gradient columns, an electret analyzer, and a spin coater. Facilities for the determination of molecular weights and molecular weight distributions by size-exclusion chromatography are also available.

Surface Science Facility
This facility is open to all qualified users interested in surface characterization. It contains a scanning Auger microprobe with submicron resolution and a scanning electron microscope with a solid-state windowless X-ray detector. Instrumentation for X-ray photoemission spectroscopy (XPS), secondary ion mass spectroscopy (SIMS), atomic force microscopy (AFM), and scanning tunneling microscopy (STM) is also available. Short training courses are offered throughout the year so that those who are interested can become qualified users quickly.

X-Ray Diffraction Facility
This laboratory includes 10 standard X-ray generators, four rotating anode units, and a variety of goniometers. Also available are three small-angle units, an EXAFS unit, topographic units, and equipment for work with single crystals or powders (from 2 K to 2,500 K). These units are operated from one of the many microprocessors with UNIX-based Sun workstations, part of a time-share system in the laboratory.

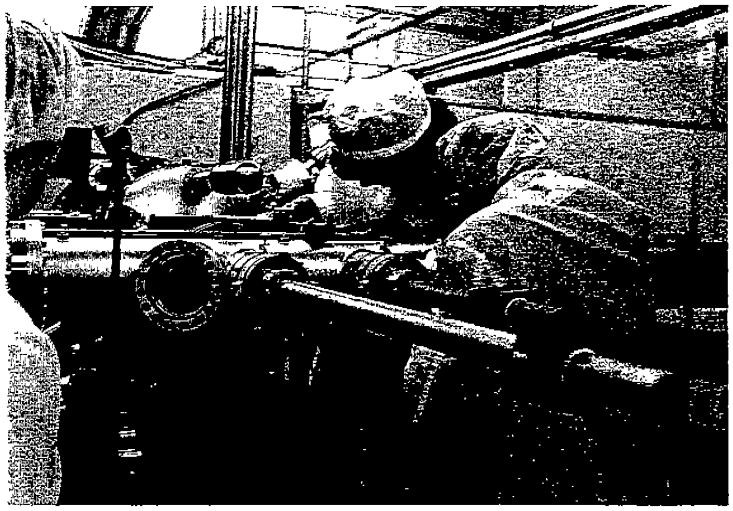
A full-time engineer assists qualified users and maintains the equipment. Several courses provide training. The laboratory staff is part of a Midwest team operating a beam line at Brookhaven National Laboratory's new high-intensity synchrotron X-ray facility, which Northwestern students may also use. It is also part of a beam line sector at the Advanced Photon Source at Argonne National Laboratories.

Other Research Facilities
Other research facilities are available for thin-film characterization (spectroscopic ellipsometer) and for measurements of charge transport, electron spin resonance (ESR), and nuclear magnetic resonance (NMR). Many other facilities are located in other departments throughout the University.

Research Facilities off Campus

DND-CAT Synchrotron Research Center
E. I. Du Pont de Nemours & Co. Inc., Northwestern, and Dow Chemical Co. have formed a collaborative access team, named DND-CAT, to design, build, and operate synchrotron radiation instrumentation at the Advanced Photon Source under construction at Argonne National Laboratories. When the facility becomes fully operational in 1996, it will serve more than 100 scientists, faculty, students, and associates.

The team will carry out research on the structure of advanced materials. Our understanding of the structure (atomic- to micron-level) is a crucial prerequisite to the development of new materials with advanced properties. Synchrotron radiation has become an essential tool in every aspect of structural analysis. This broad research program aimed at taking advantage of these new machines covers many fields of materials science and engineering. Particular emphasis will be in the study of two-dimensional or quasi-two-dimensional atomic structure, i.e., surfaces, interfaces, and thin films, as well as polymer science and technology.



Other University Resources

Computational Facilities
In addition to computing facilities within individual research groups, the department provides an ever-expanding array of RISC computers for research and classroom needs.

University Shops
Skilled instrument makers fabricate sophisticated equipment for thesis research. After appropriate training, students may work in the instrument shop on their own projects under the direction of these experts. Customized glassware or electronic devices also can be made by technicians working in the glass and electronics shops.

the Catalyst
stimulating significant action

Fall 2000
Volume 12, Number 3

Inside...

Office of the Vice President for Research

ITEC: linking research, technology, and entrepreneurs

During a visit to Northwestern last April, Governor George H. Ryan formally announced the opening of the state's first regional Illinois Technology Enterprise Corporation (ITEC) Center. The Center, which is managed by the University, will create and foster high-tech companies and jobs in Evanston and the surrounding region.

ITEC is a component of the governor's VentureTECH initiative, a five-year, $1.9 billion comprehensive strategy for investing state resources in education, advanced research and development, health sciences and biotechnology, and cutting-edge information technology programs. Funding for the Northwestern ITEC Center includes a three-year, $750,000 grant from the state and a combined $165,000 from the Kellogg Graduate School of Management, McCormick School of Engineering and Applied Science, Medical School, and Weinberg College of Arts and Sciences. In addition, the Evanston Research Park contributed $25,000.

The ITEC Center is managed by the University's Office of Strategic Initiatives (OSI). OSI was established in fiscal year 1999 to meet specific objectives cited in Northwestern University's *Highest Order of Excellence*: "strongly encourage innovation and risk-taking" and "adapt new ideas to new realities." Because a large part of the ITEC initiative involves dealing with entrepreneurs and startup business enterprises, OSI was the obvious choice to undertake the management of ITEC.

Jeff Coney, who was recently hired by OSI to serve as director of new business initiatives, has day-to-day responsibility for the ITEC Center. Coney has hired a staff of two, one staff member with a background in engineering and the other with a background in biotechnology. The staff will play an integral role in identifying high-potential business opportunities that will contribute to the Evanston area, as well as in assisting clients with commercializing technology, successfully merging business and research, and developing startup business initiatives.

Photo by Nathan Mandell

Jeff Coney, director of new business initiatives, brings his expertise as a successful entrepreneur to OSI.

ITEC staff will also effectively serve as a link between the Northwestern research community and area entrepreneurs.

Incubating and assisting faculty startups

Currently, ITEC is implementing two initiatives—to coordinate an overall strategy of faculty-initiated startups and to manage the 1801 Maple Avenue facility as a multi-use research and business incubation facility. As part of this effort, OSI has provided services and laboratory and office space in exchange for equity positions in two University-related companies, Neuronautics and SinaMed.

Neuronautics was co-founded by Lester (Skip) Binder, professor of cell and molecular biology in the Medical School. Neuronautics specializes in the treatment and diagnosis of Alzheimer's disease and related neurodegenerative disorders. The company recently received an equity investment from Fujisawa, a large Japanese pharmaceutical company.

"The University has been supportive of our company," Binder noted. "With the establishment of OSI and ITEC, I believe the University has made a statement that it is interested in being 'business friendly' to faculty-initiated ventures. Like many biotechnology companies," he continued, "we face the challenge of obtaining access to sufficient capital. The fact that Northwestern University is an equity

holder in our company enhances our credibility among potential investors. In addition, the University has introduced us to potential investors we otherwise would not have met." Binder also noted that "ITEC provides experienced advisors within the University who have 'real world' experience in creating businesses. This perspective is very important because, as a rule, university faculty have little idea of the risks and pitfalls involved in starting a company."

SinaMed was founded earlier this year by Wenn Sun. Sun was the chief business development officer at the Robert H. Lurie Comprehensive Cancer Center and the University's Center for Biotechnology. She started SinaMed with the goal of marketing authoritative and comprehensive on-line professional content and services to Asian healthcare professionals.

"I have found that being affiliated with a university gives me additional credibility that can help open doors," Sun stated. "Also, it is important to have a home base. There are colleagues to bounce ideas off of and the infrastructure support has been good for me."

Sun also noted that "there are many benefits to the University that come from encouraging and supporting entrepreneurial activities, such as attracting and retaining desired faculty and researchers. Also, from a financial perspective, royalties from licensing university technologies are an important source of revenue growth at many research-oriented universities. Finally," she concluded, "these activities are important to students who desire part-time career related employment."

This past March, Jeff Coney joined the University's Office of Strategic Initiatives as the director of new business initiatives. As part of this responsibility, Coney will manage the regional ITEC Center located in Evanston. Prior to joining the University, Coney spent 15 years as a local software entrepreneur. He co-founded Facility Management Systems, Inc., a software company, which was sold in 1996. He has also had prior employment with the City of Chicago and Arthur Andersen. Coney, who resides in Evanston, holds B.A. and M.B.A. degrees from Northwestern and is a C.P.A.

While the founders of both companies are highly skilled in their respective areas, they were in need of some hands-on help in certain aspects of starting a company. ITEC has been able to provide them with assistance in business plan development, business strategy, and introductions to venture capitalists. In addition, both companies have set up offices in the 1801 Maple building. ITEC would like to enter into similar arrangements with four to six companies per year.

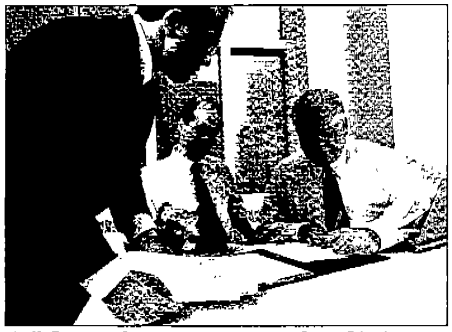


Photo by Nathan Mandell

Jeff Coney, Sam Khatami, and Skip Binder discuss Neuronautics business strategy.

Providing further assistance for entrepreneurs

ITEC has provided meaningful assistance for a varied selection of entrepreneurs.

A biotech company wanting to commercialize a product used in forensic testing sought ITEC's assistance. The company's principals were scientists, and they needed a comprehensive sales and marketing strategy to launch the product successfully. ITEC mapped out the key milestones that would be part of the sales and marketing strategy, then sought out and interviewed a number of consultants with relevant experience. The consultants submitted proposals, from which three were chosen and presented to the company. The company is presently reviewing these proposals and is expected to make a decision soon.

ITEC assisted a faculty-initiated startup desiring business plan help, office space, and startup capital. A University faculty member was attempting to commercialize a software product that resulted from a research grant. While the faculty member prepared a comprehensive business plan, he needed assistance in how to present the financial projections effectively. ITEC worked with him to reformat the projections in a more meaningful way. In addition, ITEC circulated the business plan to three venture capitalists who have a prior history of making early-stage investment in university-related companies. Finally, ITEC offered the company space in the 1801 Maple building.

With ITEC's assistance, a Colorado-based company considering a relocation to Illinois is now working with the University's Center for Advanced Cement-Based Materials to develop a cement wall product to be used in home construction. This product would be based on technology developed at Northwestern. The product uses a significant amount of fly ash, which is a coal-fired power plant waste byproduct. The company is in the process of deciding where to locate a pilot plant. ITEC has met with the company's principals and made them aware of the Illinois Coalition's Technology Development Bridge Program, that provides early stage Illinois companies access to capital.

Reaching out

ITEC's immediate plans include an outreach program to University schools and colleges to inform them of the services provided by the ITEC Center, including assistance with development of business models, business plans, and marketing plans. Counseling will also be provided in the areas of new company creation and startup business strategy and execution.

The ITEC Center will also present selected companies to the Illinois Coalition's Technology Development Bridge Program, an existing state program funded by the Illinois Development Finance Authority (IDFA). The purpose of the program is to provide seed capital to early stage Illinois-based companies. Under this program, a company can receive up to $400,000 in equity capital. The program requires that the applying company has already received an equity investment from an accredited investor. The IDFA equity investment matches the existing equity investment on a dollar-for-dollar basis.

Coney is anxious to author further "success" stories from in and around the University community and is "ready to talk with anyone interested in the ITEC initiative." Contact Coney, director of new business initiatives, at 847/491-7600 or itec@northwestern. edu with opportunities, questions, or comments.

Chemical Vapor Deposition

Northwestern University
ACTG
Advanced Coating Technology Group
Materials Technology Laboratory

CVD Thermal, Metalorganic, and Plasma Methods

CVD provides exceptional throwing power (the ability to coat complex substrates such as porous structures, 3-D shapes, and blind holes) compared to other coating processes, and produces high quality and highly adherent coatings for complex objects. By using metalorganic (MOCVD) or plasma (PCVD) methods, ceramic and metal coatings can be applied to plastics, tempered metals, and other temperature sensitive substrates.

CVD is a flexible processing technique for producing high-purity materials, protective coatings, powders, powder and fiber coatings, and composite structures. CVD technology is especially valuable for coating or infiltrating complex shapes, such as the inside of tubes, powders, porous substrates, and extended surfaces.

The breadth of ACTG's CVD capabilities and experience makes it unique among contract research organizations. ACTG specializes in

- Coating of complex 3-D substrates, such as turbine blades
- Coating the inner surface (or all surfaces) of tubes
- Metal oxide coatings for corrosion protection, composite interfaces, thermal barrier coatings, fuel cells , sensors
- Optical coatings
- Metal and ceramic coatings on temperature-sensitive substrates via MOCVD and PCVD
- Infiltration of porous media and fibrous preforms

ACTG's recent CVD work involves the development of alumina coatings using a metal-organic precursor material. The process offers dense, smooth, uniform, and continuous coatings that can be deposited at high rates (micron/minute). The as-deposited coatings are amorphous in nature. Coatings have been deposited on ceramic fiber tows and fabrics, machined metal parts, and other ceramic substrates (see figure).

WHAT IS ACTG?

The Advanced Coating Technology Group (ACTG) - formerly part of BIRL - is a Materials Research and Development Laboratory at Northwestern University. It has received international recognition for its pioneering research in PVD, CVD and thermal spray coatings. More than $7 million has been invested in cutting edge R&D programs. With an extensive knowledge base, ACTG's expertise includes:

- **Coating processes and development**
- **Unique coating applications**
- **Comprehensive coating analysis and characterization**

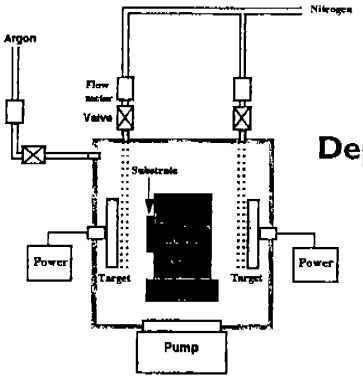
The types of coatings developed are:

- **Superhard**
- **Wear resistant**
- **Low Friction**
- **Optical**
- **Decorative**
- **Corrosion-resistant**
- **Magnetic media**

HOW AN ACTG INDUSTRIAL CONSORTIUM WORKS

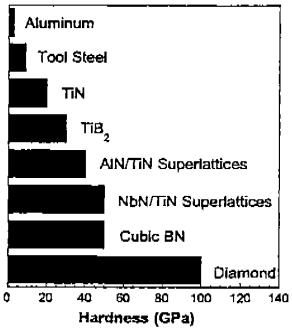
The ACTG Industrial Consortium is a unique vehicle for pooling resources and expertise of companies with parallel needs and those of our institute to accomplish practical goals. The members will be the first to take advantage of new coatings design, modeling and prediction techniques, greatly reducing the cost and time-to-market, making development much more efficient.

DESIGN RELATIONSHIPS



Deposition

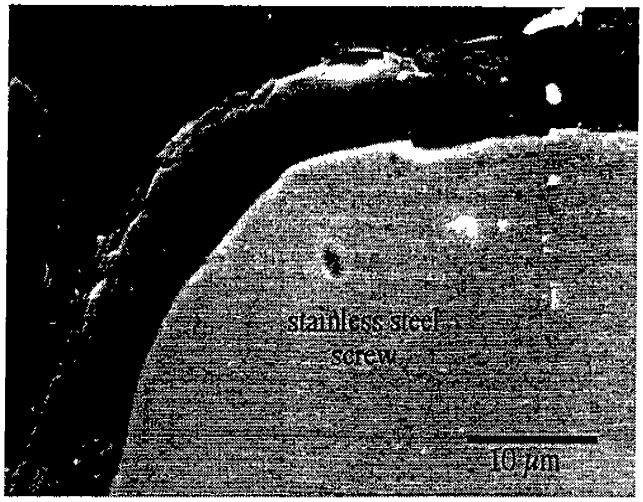
Structure



Properties

Performance

Chemical Vapor Deposition



SEM micrograph showing conformal coverage of alumina coating (deposited by MOVCD) around a stainless steel screw thread

The method is especially suitable for coating objects that are 3D-shaped containing small vent-holes such as turbine blades. The process also offers the advantages of low cost, high efficiency, and high throughput with minimal investment for scrubbing of gaseous byproducts. The MOCVD precursor is atmospherically stable and is commercially available at relatively low cost ($120/pound). In the current set-up, objects with dimensions upto 3"x3"x 6" can be coated uniformly.

Alumina coatings can be useful for a variety of applications including corrosion protection, composite fabrication, electrical insulation, optical coatings, dielectric coatings, and thermal protection. Based on the mutual level of interest, ACTG may offer to coat small samples free of cost for your evaluation.

ACTG has also developed a cold-wall MOCVD process for developing yttria-stabilized zirconia (YSZ) coatings. YSZ coatings are being used for a variety of applications including fuel cells, superconductor applications, gas sensors, pH sensors, and other high temperature applications.

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Northwestern University

Advanced Coating Technology Group
Materials Technology Laboratory

Small Particle Plasma Spray

Northwestern University
Advanced Coating Technology Group
Materials Technology Laboratory

SPPS

A unique plasma spray technology for corrosion and wear-resistant coatings

Plasma spray coatings are formed by introducing metal, ceramic, or plastic powders into a plasma flame and then spraying them onto a component. They are widely used as protective coatings for wear and abrasion. Because standard plasma spray methods only allow us to spray large particles (typically 50-200μm), they are somewhat rough and porous. Consequently, traditional plasma sprayed ceramics are almost useless for corrosion protection (one of the largest potential markets), because liquids and gases reach the underlying surface through interconnected open porosity.

ACTG has developed a new small particle plasma spray (SPPS) technology that for the first time makes it possible to spray 0.5 - 10μm ceramic or metal particles to produce corrosion resistant, wear resistant, or even decorative coatings over large areas. ACTG's SPPS technology is the only small-particle spray method currently on the market and is available for evaluation and licensing.

ACTG's SPPS technology incorporates two critical patent-pending inventions that make SPPS possible:

(1) equipment for feeding fine powder without clogging or pulsing,

(2) an innovative method for injecting the powder into the plasma that ensures the proper amount of heat for optimum coating.

The properties of SPPS coatings are far superior to those of standard plasma spray coatings. Although the easiest materials to spray are oxides such as alumina and zirconia, the method is by no means limited to oxides, or even to ceramics. SPPS coatings have far superior properties to standard plasma sprays. They are typically

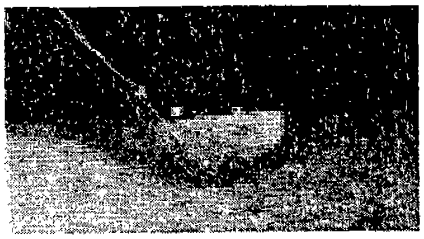
- 99+% dense with tailored closed porosity
- Impermeable to water and gas
- Smooth and thin (continuous coatings from several mils down to 5μm)
- Flexible - thin coated steels can be bent without damage to the coating
- Characterized by high dielectric strength
- Able to provide thermal management through graded structure and closed porosity

Small Particle Plasma Spray

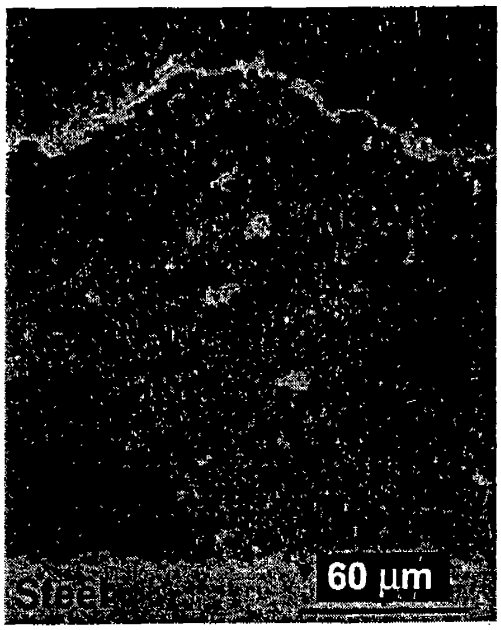
While standard plasma sprays are thick and porous, SPPS coatings can be made thin and impermeable. This unique gas and liquid barrier property has been exploited in several applications. In solid oxide fuel cells, a 15 μm thick layer of impermeable oxide is sprayed by SPPS onto a porous electrode. Continuous fiber ceramic-matrix composites can be protected from corrosion by a thick layer of co-sprayed large-particle and SPPS alumina. This techinique combines the advantages of rapid build-up provided by standard plasma spray with the corrosion resistance provided by SPPS.

SPPS coatings will open up the market for thermal spray coatings to include

- Corrosion protection
- Microlaminate thermal barrier coatings
- Coatings for extreme wear and erosion
- Wear and erosion protection of flexible components
- Decorative coatings for consumer items
- Electrical insulation
- Sensors and fuel cells



Water bead on a dense SPPS deposited alumina coating



Dense alumina coating deposited using the ACTG SPPS technology

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Northwestern University
Advanced Coating Technology Group
Materials Technology Laboratory

Thermal Spray

Northwestern University
Advanced Coating Technology Group
Materials Technology Laboratory

Thermal Spray

Thermal Spray (TS) is one of the most widely-used coating technologies for protecting components in harsh environments. It is primarily used to apply thick metal and ceramic coatings cost-effectively over large areas. ACTG (formerly BIRL), however, specializes in developing new TS methods and adapting them to new markets.

Thermal spray is the generic term for a wide range of techniques for spraying solid particles onto a surface (see figure). Material in powder, wire, or rod form is inserted into a hot region, where droplets form in either a molten or plastic state. These droplets are accelerated in a gas stream onto the substrate, where they bond to form a protective coating. TS coatings are used commercially for applications including wear, corrosion, and thermal management.

Flame Spray In flame spraying, powder or wire is fed into an oxygen-fuel flame. The flame melts the particles and drives them toward the substrate. Flame-sprayed coatings are typically of lower quality and less density than those sprayed by other thermal spray processes, and are primarily used for repair and dimensional restoration of metal components.

Electric Arc In this process, an electric arc is struck between two wires, vaporizing them while a gas jet atomizes the metal and accelerates the molten particles toward the substrate. In the electronics industry, the electric arc process is used in the coating of plastic electronic enclosures for EMI/RFI protection. This process is most often used to protect steel structures from corrosion or oxidation. Spraying zinc, aluminum, or alloys of both onto bridges provides protection from corrosion for periods two to five times greater than typical paint coatings.

Plasma Spray Because plasmas provide higher temperatures than flames, plasma spray is used for depositing oxide ceramics and other high-temperature materials. An arc struck between a stick cathode and a ring anode provides the plasma source. Argon or nitrogen (often augmented by hydrogen or helium) flows through the arc, where it is heated to form a plume whose centerline temperature can exceed 10,000°K. Powder is injected into the plume, where it is softened or melted and accelerated toward the substrate.

Thermal Spray

Plasma spray is the principle technology used for erosion and thermal-barrier coatings in jet engines, with a typical jet engine having between 600 and 2,000 plasma- sprayed parts. Plasma spraying is also heavily used in the automotive, biomedical, defense, petrochemical, and printing industries.

Small Particle Plasma Spray (SPPS) ACTG has developed and patented a new small particle plasma spray technology that for the first time makes it possible to spray 0.2-30 μm ceramic or metal particles to produce corrosion-resistant, wear-resistant, or even decorative coatings over large areas. ACTG's SPPS technolgy, which is the only small particle plasma spray technolgy currently on the market, is available for evaluation and licensing. The invention of SPPS has pushed TS into broader markets closed to conventional TS technology.

ACTG works with a variety of government and industrial clients. Our research scientists continue to develop new processes and equipment, as well as coatings engineered to match customer products and markets.

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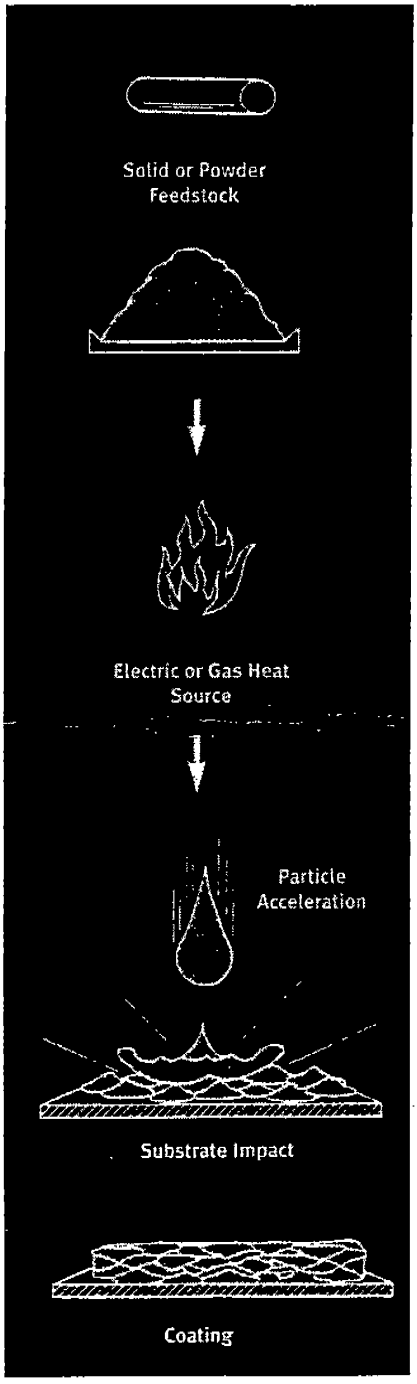
Basic elements involved in the application of thermal spray coatings.



Northwestern University

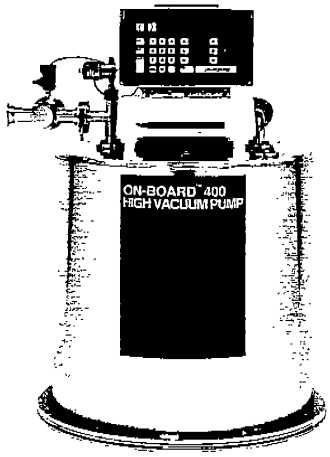
Advanced Coating Technology Group
Materials Technology Laboratory

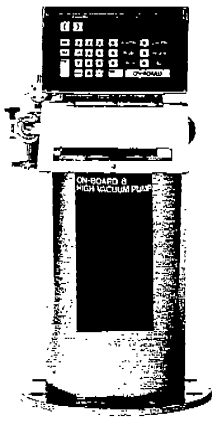
CTI-CRYOGENICS
HELIX TECHNOLOGY CORPORATION

RETROFITTING EXISTING VACUUM SYSTEMS WITH **ON-BOARD** CRYOPUMPS

Vacuum users who currently have non-**On-Board** cryopump-equipped vacuum systems can now retrofit those systems with **On-Board** cryopumps. System retrofits yield important benefits:

- *Integrated, centrally accessible pump monitoring/control.* All of the functions of each individual pump are easily controlled from a pump- or rack-mounted keypad/display, or from your host computer.
- *Central control of entire cryopump networks.* Every function of every pump in a large network of pumps is easily accessible from your host computer — temperature and pressure control, roughing and purge valves, relays, even rapid regeneration. The necessity to enter a clean room to regenerate a cryopump no longer exists.
- *Integrated diagnostics.* The **On-Board** system shows you how much up-time you're getting between regenerations, and gives you similarly detailed readouts on cooldown time, warmup time, and much more. You'll know far in advance about even the slightest tendency toward performance degradation.
- *Enhanced process control.* **On-Board** cryopump system control software can be tuned exactly to the parameters of your vacuum process, giving you unmatched productivity and performance. And the **On-Board** system's standard first-stage temperature control gives you superior performance in such processes as sputtering.
- *Faster, more thorough regeneration.* **On-Board** 8 cryopumps typically regenerate in less than 2½ hours. **On-Board** 10 cryopumps, in a little over an hour and a half. Moreover, because of regeneration technology developed for **On-Board** systems exclusively, regeneration is more thorough than ever before. The result of rapid regeneration is increased system up-time.





- *Backed by GUTS (Guaranteed Up-Time Support).* As always, if you ever have a question or need help, call 1-800-FOR-GUTS (1-800-367-4887) 24 hours a day, 365 days a year. A vacuum expert will always be there for you.

▶

DESCRIPTION

On-Board cryopump retrofit kits are available in a variety of sizes to enable vacuum users to convert their systems quickly and easily to **On-Board** pump configuration. Kits include the pump, an electrical controller designed to interface your **On-Board** cryopump with your present compressor, and any other hardware necessary for installation.

(**On-Board** pumps feature factory-integrated roughing and purge valves, rapid regeneration capabilities, integrated communications and diagnostic capabilities, and much more. For complete details on any **On-Board** cryopump, request **On-Board** pump-specific data sheets.)

Users of Cryo-Torr 8, 8F, 10, or 400 cryopumps can upgrade to **On-Board** cryopump systems by taking advantage of trade-in allowances which are offered regardless of the age of the traded CTI pumps.

Users of non-CTI cryopumps, or of oil diffusion or turbomolecular pumps, should contact CTI to determine whether their systems can be adapted to use **On-Board** cryopump systems.

CTI-CRYOGENICS also offers specialized kits for custom retrofits. For example, if your **On-Board** pump will be used in a Varian* 3180 or 3190 system, special pump hardware is required. It is included in the retrofit price and supplied as an integral part of the kit.

CTI-CRYOGENICS offers extensive applications engineering and technical support, to make your conversion to **On-Board** systems as smooth as possible.

RETROFIT PROCEDURE

Contact your nearest CTI-CRYOGENICS representative or any CTI office to be certain your current system can be upgraded to **On-Board** pump functionality.

To take advantage of the trade-in allowance, users of Cryo-Torr cryopumps issue a purchase order for the full value of the **On-Board** pump, which is billed when shipped. The serial number of the Cryo-Torr pump to be traded must be included on the purchase order for the **On-Board** pump. Your account is credited for the traded pump as soon as it has been received in Mansfield.

If your Cryo-Torr pump needs an overhaul, it may be especially advantageous to consider retrofitting your system to an **On-Board** pump instead. Not only would you save the cost of an overhaul, but your current, un-overhauled CTI pump still qualifies for a trade-in allowance toward a new **On-Board** pump.

Because so many variations exist in individual systems — flange types, cable lengths, etc. — it is impractical to list part numbers here for every possible **On-Board** retrofit kit configuration. For specifics, call our Customer Service representatives in Waltham or Santa Clara, or any CTI representative. Their telephone numbers are listed below.

CONCLUSION

On-Board cryopump systems can bring you unprecedented up-time, productivity, performance, and ease-of-use. Because they can be regenerated so fast and so thoroughly, **On-Board** pumps spend more time running, giving you unmatched productivity. Because they're built by CTI-CRYOGENICS, you know they'll keep on running. And because we spent years working with scores of users throughout the design and development of **On-Board** systems, you know they're practically effortless to use.

For more information on retrofitting your vacuum system with **On-Board** cryopump systems, call your CTI representative or your nearest CTI-CRYOGENICS office.

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CTI-CRYOGENICS
HELIX TECHNOLOGY CORPORATION

Maximize Throughput and Uniformity in Ion Implantation Through Improved Vacuum Techniques

Uniformity and throughput — two simultaneous process requirements

An important goal in semiconductor manufacturing is continual improvement in the fab's rate of output of uniform product. This means that the well-known, and individual, requirements for high process throughput and high process uniformity are, in fact, simultaneous requirements.

Of the various semiconductor manufacturing processes, ion implantation is one of the more challenging. Uniform performance in the finished devices depends strongly on implant uniformity, and implant uniformity requires tight process control. However, implanters require frequent tool PM's, and such interruptions are inherently disruptive to process control. In fact, maintaining throughput alone is a difficult task. It's not surprising that the implant operation is often a bottleneck in product flow through the fab.

While cryopumping is the preferred vacuum pumping method for ion implantation end stations, traditional cryopumping with manual regeneration presents a throughput challenge to implant users. The cryopumping technique we describe below effectively eliminates regeneration as a throughput detractor. It has the additional benefit of simultaneously improving implant uniformity.

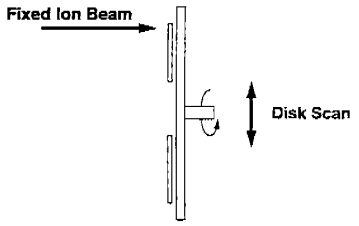
The result is maximized output of uniform product — and reduced cost per wafer of high quality devices.

Managing hydrogen for more implant uniformity carries a throughput cost

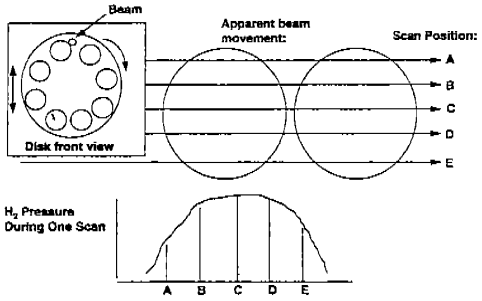
Large quantities of hydrogen are released by the energetic reaction between the ion beam and the pattern-delineating photoresist on the wafers. As implant users move to higher implant currents and energies (driven by both throughput motivations and device design requirements), hydrogen generation rate, Q, rises significantly as a result.

Q varies during each implant batch. For example, in a high-current implanter, Q varies as the wafers are repeatedly scanned through the beam path. This causes a proportionate variation in hydrogen partial pressure P in the beam path, because P (Torr) is related to Q (Torr-liter/sec) by the approximation P = Q/S, where S is the hydrogen speed of the pumping system (in liters/sec). The effect is illustrated in Figure 1.

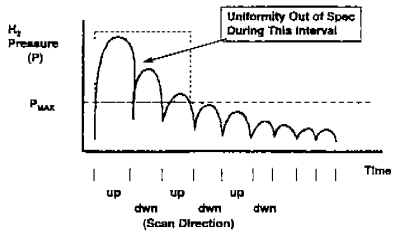
Fig. 1
In a high-current implanter, the disk scans the wafers through the ion beam . . .



. . . releasing hydrogen
in proportion to the length of the beam's path
across coated wafer surface.



Repeated scans produce repeated peaks
in hydrogen generation rate Q,
and therefore, in hydrogen partial pressure P.



High and varying P (which often reaches into the 10^{-4} Torr range for high-current implanters) causes varying degrees of beam neutralization and other effects. These produce dose variations, and compromise implant uniformity. Since reducing P reduces these effects, implant users often associate a maximum level of P (i.e. P_{MAX}) with the maximum dose variation they will tolerate. A common technique for maintaining implant uniformity within the desired tolerance is to temporarily reduce beam current (or block the beam) when P exceeds P_{MAX}. Reducing the beam current slows the hydrogen generation rate. Unfortunately, it also reduces the implantation rate, and increases batch processing time.

The solution is to maximize hydrogen pumping speed

Since P = Q/S, increasing S will reduce both the magnitude of P, and the variation in P, for any Q. (It will flatten out the pressure profile illustrated in Figure 1). Reducing P and its variation will reduce dose variations — therefore, increasing S is beneficial for implant uniformity.

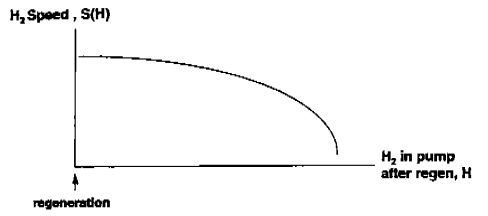
Cryopumping is the fastest means for pumping hydrogen in the pressure range of interest. But cryopump capacity for hydrogen is finite, and therefore, cryopumps must be regenerated periodically. Because hydrogen is by far the largest gas by-product of the ion implantation process, it is the principal driver of cryopump regeneration frequency.

Traditional cryopumps take hours to regenerate, consuming the better part of a production shift for each regeneration — a significant throughput consideration. Historically, the user's only recourse for maintaining acceptable throughput has been to try to maximize the time between regenerations — a typical goal might be to go for up to a month between regenerations. Taking this approach, it is natural to assume that higher hydrogen capacity in the cryopump would prove advantageous to process productivity.

Infrequent regenerations compromise uniformity gains for the sake of throughput

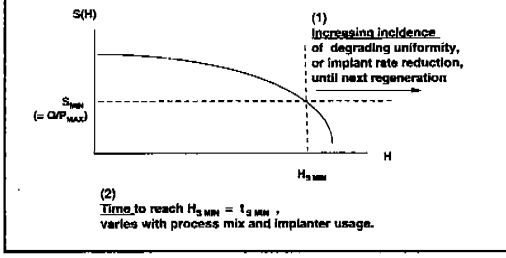
However, this approach, while intuitive, has serious shortcomings. The reason is that any cryopump, no matter its capacity, experiences significant fall-off in the parameter which is critical for implant uniformity — hydrogen speed — well before a month of use has elapsed. This occurs because the cryopump's charcoal begins to fill with hydrogen immediately upon resuming implanting after regeneration. As it fills, it is progressively less and less able to cryoadsorb hydrogen at its initial rate, and the result is that the pump's hydrogen speed falls off. Figure 2 illustrates the relationship between cryopump hydrogen pumping speed S(H) and the quantity of hydrogen H accumulated in the pump's charcoal since the previous regeneration.

Fig. 2
Hydrogen pumping speed, S(H), falls as the quantity of hydrogen in the pump, H, increases after regeneration.



This speed fall-off has significant implications. Remembering that P = Q/S, we can define a minimum pumping speed $S_{MIN} = Q/P_{MAX}$ needed to maintain desired implant uniformity in the presence of any specific value of Q (Figure 3).

Fig. 3
S(H) falls below S_{MIN} when the quantity of hydrogen in the pump reaches $H_{S\,MIN}$.



As soon as the pumping speed falls below this level, the user must accept an increased incidence of reduced implant current as P fluctuates above P_{MAX} in response to Q fluctuating across each batch. The alternative is to increase P_{MAX} and accept reduced implant uniformity. Worse, the rate of incidence of these conditions will increase as S continues to drop before the next regeneration. For good reason, the time after regeneration for S to drop to S_{MIN}, $t_{S\,MIN}$, can be thought of as the effective hydrogen capacity of the pump.

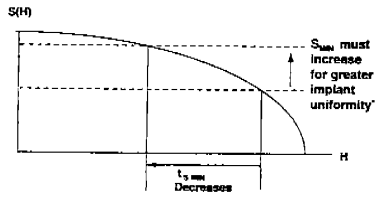
S_{MIN} is determined by the quantity of hydrogen $H_{S\,MIN}$ in the pump. Since all the process-generated hydrogen ends up in the pump, $t_{S\,MIN} = H_{S\,MIN} / Q\,av$, where Q av is the average

hydrogen generation rate during $t_{S\ MIN}$.* Therefore, the pump's effective hydrogen capacity, $t_{S\ MIN}$, varies with Q av.

Q av, in turn, varies from week to week with the rate of implanter usage, and with the variation in hydrogen generation rate for each different process recipe and batch run on the implanter. This means that the effective pump capacity is not predictable, but is dependent on the specifics of tool usage. This, in turn, presents the risk of unexpected exposure to reduced implant current or reduced uniformity, possibly necessitating unscheduled cryopump regeneration to restore acceptable operating conditions.

The problem is greatest for users who wish to increase the uniformity of their implant processes. These users must set P_{MAX} at progressively lower levels to reduce dose variation. Because $S_{MIN} = Q/P_{MAX}$, they must therefore require higher S_{MIN}. Looking at Figure 4, we can see that for these users, the pump's effective hydrogen capacity $t_{S\ MIN}$ can become quite small — independent of its specified capacity.

Fig. 4
For greater implant uniformity, S_{MIN} must increase. This reduces the pump's effective capacity ($t_{S\ MIN}$).



*$S_{MIN} = Q / P_{MAX}$. For more implant uniformity, P_{MAX} must decrease.

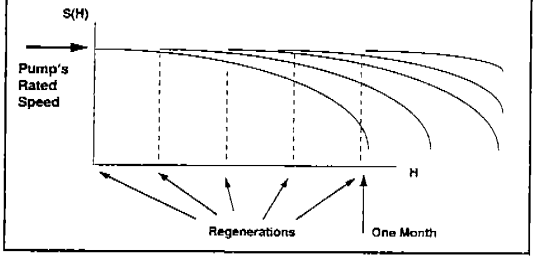
In summary, infrequently-regenerated cryopumps of any specified capacity experience speed fall-off as they fill with large quantities of hydrogen between regenerations. This places arbitrary limits on attainable implant uniformity, and does not effectively prevent unscheduled throughput problems.

A better alternative — regenerate MORE frequently

The source of the problem is the length of time (which is measured in hours) required to regenerate a traditional cryopump. The use of second stage regeneration, in On-Board® Cryopumps with FastRegen™ Control, offers an attractive alternative approach. On-Board second stage regeneration is as effective at recovering full hydrogen pumping speed as is traditional cryopump regeneration, but only takes about one hour. This creates the opportunity to keep S above S_{MIN} indefinitely, and without an implanter throughput cost — specifically by regenerating during implanter source changes, which are typically executed once or twice a week. (Full pump regeneration can be reserved for monthly source PM's, which typically take 5-8 hours).

As shown in Figure 5, this strategy fulfills the fundamental requirement of the implant process — it effectively maintains the full rated speed of the pump continuously. By minimizing P, this technique maximizes implant uniformity on a week-to-week basis. It minimizes the frequency of beam current reduction for any chosen P_{MAX} - i.e., for any desired level of implant uniformity. Further, it makes the system's performance immune to variations in tool usage and process mix (Q av), reducing the potential for unscheduled regenerations. And, it does these things without imposing a tool throughput cost for scheduled cryopump regeneration.

Fig. 5
On-Board® Cryopumps with FastRegen™ Control allow second stage regeneration during weekly source changes. This maintains the full rated speed of the pump indefinitely.



Conclusion

Cryopumping continues to offer the highest hydrogen pumping speed — a critical requirement for ion implantation. With the technique we've described, the need for cryopump regeneration can be met without tool throughput cost, and without the conflict between tool throughput and implant uniformity which exists for infrequently-regenerated cryopumps.

Used in this way, the cryopump is no longer a capacity-limited device. This is an ideal vacuum scenario for maximizing the output of uniform product from the implant process — and for reducing the cost per wafer of high quality devices.

Improved Pumping Strategy for Ion Implanter End Stations

Philip A. Lessard, Gary S. Ash, Robert Unger
CTI - Cryogenics, Mansfield, MA, USA

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Improved Pumping Strategy for Ion Implanter End Stations

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Abstract - The variety and complexity of ion implants required in modern semiconductor fabrication has placed increasing burdens on high vacuum pumps on the end stations of implanters. More high energy and high current implants, combined with increasingly stringent process requirements for greater uniformity of implant and higher product throughput, mean a requirement for a pumping scheme that yields high speed (and, more importantly, constancy of speed), while maintaining high tool availability.

In this paper, we trace the logic that leads to these requirements and describe the resultant pumping scheme that uses high hydrogen speed cryopumps, a regeneration scheduling strategy that minimizes tool downtime, and improved regeneration methodologies that restore full pump capacity and speed in minimum time. When applied to operating fab tools, these techniques have resulted in significantly increased implanter availability, as well as improved process results.

I. Introduction

When photoresist coated wafers in ion implanters are hit with the energetic charged particle beam, chemical bonds in the hydrocarbon based resist are fractured. Most of the resultant gas load is hydrogen [1,2]. If this gas load is not pumped effectively, beam interaction with the neutral species will lead to implantation of undesirable species or miscounting of implant dose [3]. The actual gas load is a complicated function of implant type, energy, dose, and time. The gas load typically decreases with time for lower energy implants as the resist is carbonized, but in high energy implants, the total implant time is usually short enough that the outgassing is high and constant.

• *Statement of the Problem*

Cryogenic vacuum pumps are universally used for implanter end station pumping because of their very high hydrogen speed and low life cycle cost. Since cryopumps are capture pumps, and pump hydrogen by cryoadsorption [4], their hydrogen speed will change (decrease) as the adsorption sites are occupied. From a user perspective, this process variability is undesirable. Further, this decrease in speed implies that cryopumps must be regenerated periodically. This has traditionally been a significant detractor from implanter availability. Since there are various organic byproducts from the photoresist bombardment that enter the pump, complete and effective regeneration may take longer than in other semiconductor manufacturing processes.

II. Cryopump Performance Characteristics

Cryopumps remove hydrogen from a vacuum system by adsorption on a high-surface-area adsorbate, usually charcoal, maintained at a very low cryogenic temperature, preferably about 13-14K [4]. As adsorption sites are occupied, the hydrogen molecules take longer to find an unoccupied absorption site, and pumping speed decreases. If there were no conductance losses from the source of hydrogen to the charcoal, this speed falloff would be (to a first approximation) a linear function of the quantity of hydrogen in the charcoal. Pump and system geometries reduce conductance, flattening the curve and creating a more desirable constancy of speed, but only at the expense of the magnitude of the speed. In other words, as the pump geometry is optimized for fundamental speed, the linearity of the speed change is accentuated.

It is vital to understand this fundamental limit to available pumping speed. No matter what is done internally to the pump to raise its speed or make it more constant, we cannot exceed the theoretical limit of cryopump inlet size. At some point, if a system needs more speed, more pumping area must be provided by system design (i.e., more or bigger pumps).

As an alternative approach, one can maintain the pump's hydrogen speed by regenerating more frequently and effectively. To this end, we have examined various regeneration schemes with the goal of making the process "painless" and consistent to the tool user.

• *Testing Methodology*

Pumps were installed on a suitably sized speed dome constructed in accordance with preliminary AVS

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specifications [5]. Flow meters were molecular flow elements calibrated by the positive displacement 'bubble' method. Bayard-Alpert ionization gauges measured vacuum levels. They were calibrated for hydrogen using the steady flow method [6].

After establishing a base pressure of approximately 1xE-08 torr, we set the flow of hydrogen such that a steady pressure of 2xE-05 torr resulted (rendering the exact base pressure moot in the speed calculation). We then flowed hydrogen steadily, recording pressure continuously, until the pressure doubled (or speed halved). The amount of hydrogen taken in is the pump's capacity. The actual speed is the ratio of hydrogen flow to (corrected) [6] hydrogen pressure.

This test does not precisely reflect actual field use, where hydrogen generation rate fluctuates within and between implants. It does, however, provide a repeatable and transferable benchmark for characterizing cryopump hydrogen pumping, for comparative performance testing, and for failure analysis.

Figs. 1 and 2 show the result of this test for 8" nominal (7.88" i.d.) and 10" nominal (11.5" i.d.) cryopumps. The data points denoted "FULL" reflect hydrogen speed vs. hydrogen capacity following a complete regeneration of the pump.

III. Regeneration

In traditional implanter use, pumps are pushed to their capacity limit - until a suitable base or recovery pressure cannot be reached. Then the pump is regenerated by warming, purging and conditioning, then cooling and returning to service. This regeneration process takes a considerable amount of time. The exact time depends (at least) on how often regenerations are done, how 'dirty' the pumps are from organic byproducts from the photoresist, types of implant, and quality of regeneration. Regeneration times range from an optimistic 2 1/2 hours to a more typical 4-6 hours.

In order to reduce this time, it is possible to employ a specific regeneration process that avoids warming the pump to ambient temperature, but cycles cryopump arrays to temperatures sufficient to evolve and dismiss the hydrogen and other gases pumped on the coldest part of the pump (the second stage), but not to evolve water or other species pumped on the warmer first stage of the pump. This "fast regeneration" scheme allows regeneration in approximately one hour.

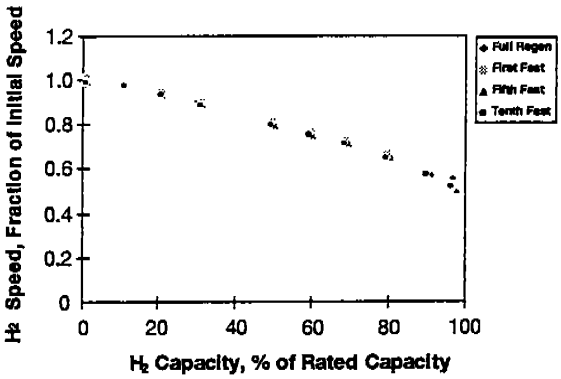

Fig. 1. Hydrogen speed vs. capacity following successive fast regenerations 10" cryopump

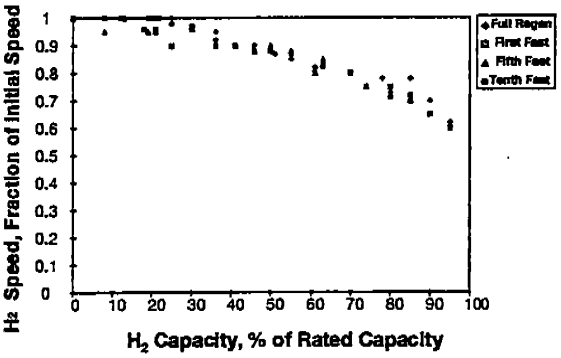

Fig. 2. Hydrogen speed vs. capacity following successive fast regenerations 8" cryopump

- *Effect of Second-Stage Regeneration on Hydrogen Performance*

To assure that the fast regeneration scheme does not adversely impact hydrogen performance, we repeated the hydrogen speed versus capacity test described above on two cryopumps, following each of 10 such regenerations. As shown in Figs. 1 and 2, the second-stage regenerations had no adverse affect on hydrogen performance.

- *Best Operation*

These results indicated that we could optimize cryopump usage in a fab by doing fast, second-stage regenerations often - for instance, during scheduled source changes - with the major benefit that cryopump performance would be constant because performance remained on the flat part of the curve. By not filling the pump more than a quarter to half full,

speed for hydrogen does not decrease appreciably, taking out a process variable.

In addition, downtime due to exclusive reliance on the lengthy full regeneration decreases. Data from an operating wafer fab, Fig. 3, shows an increase in uptime of 75 hours per month on a high-current implanter following adoption of this scheme. Following a short learning curve, downtime due to regeneration is nil. This experience has been extended now for over a year. Data obtained by another user showed a substantial reduction in implant dose variation as well, the result of better maintenance of the pump's full hydrogen speed. [7]

• *Dealing with the other pumped species*

While H_2 is the predominant gas load, and is hence the key species which creates dosimetry errors, endstation cryopumps contain other species as well. We have examined the residue in several implanter cryopumps. There are many complicated hydrocarbon fragments, most with melting points lower than water. If not dealt with effectively, these can compromise cryopump performance as time goes by, increasing the time required for full (i.e., both first and second stage) regeneration, and potentially compromising pumpdown performance. To address these issues, we examined the full regeneration process in detail.

Full (first- and second-stage) regeneration typically consists of warming the pump, purging with a dry gas (usually nitrogen) for an extended period, testing that the pump is clean, and then cooling to cryogenic temperatures. We examined various combinations of roughing, purging and array heating, using the cryopump's microprocessor control, with pressure and temperature feedback. As a simple reference test, we added 5 liquid cc. of water to a pump and roughed and purged at various vacuum levels. The figure of merit was time to eliminate the water (we could see the puddle). As shown in Fig. 4, the time to eliminate the water is a strong positive function of vacuum level, being about 8 times faster at 5 torr than at ambient. Adding heat to the arrays with the in-place electrical heaters also aids in water removal.

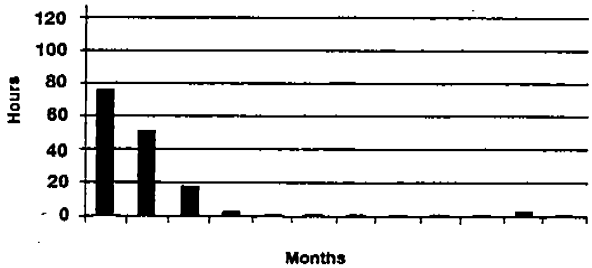

Fig. 3. Monthly Hours of Implanter Downtime Due to Cryopump Regeneration (showing the effect of changing to fast regenerations during source change month 2).

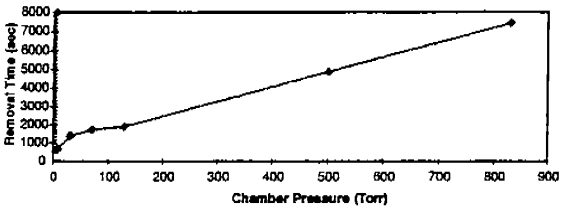

Fig.4. Volatiles removal time vs. chamber pressure.

This full regeneration scheme is now in extensive field testing and so far has reduced full regeneration times by, on average, a factor of 1/2 to 1/3 on a variety of implanters.

IV. Summary

Cryopumps provide high pumping speeds which are critical for maintaining proper vacuum levels on ion implanter end stations. In order to optimize their inherent pump speed advantages, we propose the following revised regeneration procedure:

- Perform fast second-stage regenerations during source changes. This maintains constancy of hydrogen pumping speed, eliminating a process variable, while minimizing downtime due to regeneration.

- At an appropriate scheduled maintenance interval (e.g. monthly source PMs), perform a full first- and second-stage regeneration. This cleans the pump of water and residual hydrocarbon byproducts.

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[7] Michael Rendon, private communication.

Basic Vacuum Practice Course

Course Description

The Basic Vacuum Practice course is an excellent source of practical information on vacuum system operation and maintenance as well as a good review and update on vacuum technology. Following a discussion of basic vacuum concepts, you will take an in-depth look at the pumps, gauges, and hardware components used in most diffusion, cryo, ion, TSP, and turbo-pumped systems.

You will gain the practical knowledge to operate and maintain your system properly and keep it up and running with minimum downtime and lower maintenance costs. This results in improved productivity and greater job satisfaction.

As a course participant, you will receive the Basic Vacuum Practice training manual. The manual is an excellent source of practical information.

Course Outline

Vacuum Fundamentals
- Nature of vacuum
- Large and small numbers
- Temperature
- Pressure
- Gas laws and gas flow
- Pumping speed and throughput

Roughing Pumps
- Pressure ranges of pumps
- How pumps are teamed up

High-Vacuum Pumps
- Oil diffusion pumps
- Baffles and traps
- Turbomolecular pumps
- Cryopumps

Vacuum Materials and Hardware
- Materials
- Joining techniques
- Components

Systems
- Evaluating systems
- Building and operating a system
- Characterizing system performance
- And vacuum integrity

Ultra-high Vacuum Pumps
- Titanium sublimation pumps
- Non-evaporative getter pumps
- Ion pumps

Troubleshooting
- Categories of faults
- Vacuum pumps
- The vacuum system

Gauges
- Direct force measurement
- Thermal conductivity
- Ionization

Leak Detection
- Problems that appear to be leaks
- Sizes of leaks
- Methods of leak detection
- Calibrated leaks and measurement
- Welding techniques and leaks

After You Finish This Course:

- You will have a more thorough understanding of basic vacuum concepts.
- You will understand the importance of proper vacuum practice and its relation to achieving and maintaining desired pressures.
- You will be able to recognize the similarities and differences between rough, high, and ultra-high vacuum usage and techniques.
- You will be able to determine the advantages/disadvantages of several vacuum pumping methods for your application(s).
- You will know the general troubleshooting approach to vacuum system problems.
- You will be able to perform leak detection using several techniques.

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Leak Detector Applications & Techniques

Course Description

This course is designed primarily as an introduction to helium leak detection. Excellent for equipment operators, this intensive two-day course addresses the advantages and limitations of various leak detection techniques and explores ways to get the best performance from a helium mass spectrometer leak detector. Operation, tuning, and calibration of the detector are covered in practical laboratory sessions. Leak detection methods designed to meet various problems and system configurations are discussed and demonstrated. Different approaches are offered for solving those tough application problems that arise when the leak detection equipment can not be used in the normal manner.

Upon completion of the course the student will be able to operate, tune, and calibrate a leak detector. The student will also understand how to perform the different methods of leak detection correctly.

Course Outline

Theory
- Vacuum concepts
- Leak detector concepts
- How the spectrometer tube works
- Leak detector rate measurements

Operation
- Description of controls
- Tuning*
- Calibration*
- Rate meter reading*

Test Procedures
- Fine test procedures**
- Gross leak procedures**
- Component leak checking**
- System leak checking**
- Sniffer probing**

* Lecture and lab
** Semi-customized to meet class needs
- Maintenance

Prerequisite: Basic Vacuum Practice

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Leak Detector Operation and Maintenance Course

Course Description

This courses are primarily designed for personnel responsible for the maintenance of leak detectors. The proper use and operation of leak detectors is emphasized. The 3-day leak detector maintenance course covers Varian leak detectors with analog electronics (938, 94X, 95X, 960, 990 CLD). The 2-day leak detector maintenance course covers Varian leak detectors with digital platform electronics (94X, 979, 960, 990 dCLD).

We begin our classes with a discussion of the advantages and limitations of various leak detection techniques and explore ways to get the best performance from a helium mass spectrometer leak detector. Leak detection methods designed to meet various problems and system configurations are demonstrated and taught in our training lab. Operation, tuning, and calibration are also covered. We involve the student in hands-on troubleshooting and calibration procedures of the leak detector.

Upon completion of these courses, the student will be able to disassemble, clean, troubleshoot, and maintain this equipment effectively and therefore minimize system down time.

Course Outline

Theory
- Vacuum fundamentals
- Leak detector components
- How the spectrometer tube works
- Leak rate measurements

Mechanical Vacuum Pump
- How it works
- Maintenance

Diffusion and Turbo Pumps
- How it work
- Why it is needed
- Tolerable foreline pressure
- Maintenance

Spectrometer Tube
- How it works
- Tuning and calibration controls
- Operation
- Maintenance

Electronics (varies with models)
- Valve control circuits
- Power supplies
- Vacuum gauge calibration

Hands-on Laboratory
- Tuning and calibration
- Electronics adjustments
- System disassembly and cleaning
- Troubleshooting

Course is available on-site, where equipment normally is provided by the customer

Recommended prerequisite:
Basic Vacuum Practice
Leak Detection Applications and Techniques

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(781) 861-7200 Fax: (781) 860-5405

ISO 9001

4-Day Combined Basic Vacuum Practice with Leak Detection Application and Techniques

Course Description

These 4-day courses combine our two most popular courses, the Basic Vacuum Practice and Leak Detection Applications & Techniques into one short, cost-effective course. A turbo-pumped high vacuum system and leak detector will be provided for hands-on activities. See the individual course descriptions for more information.

Course Outline

- **Vacuum Fundamentals**
  - Nature of vacuum
  - Large and small numbers
  - Temperature
  - Pressure
  - Gas laws and gas flow
  - Pumping speed and throughput
- **Roughing Pumps**
  - Pressure ranges of pumps
  - How pumps are teamed up
- **High Vacuum Pumps**
  - Oil diffusion pumps
  - Baffles and traps
  - Turbomolecular pumps
  - Cryo pumps
- **Ultra-high Vacuum Pumps**
  - Titanium sublimation pumps
  - Non-evaporative getter pumps
  - Ion pumps
- **Vacuum Materials and Hardware**
  - Materials
  - Joining techniques
  - Components
- **Systems**
  - Evaluating systems
  - Building an operating system
  - Characterizing system performance and integrity
- **Troubleshooting**
  - Categories of faults
  - Vacuum pumps
  - The vacuum system
- **Gauges**
  - Direct force measurement
  - Thermal conductivity
  - Ionization
- **Leak Detection**
  - Leak detector basics
  - Leak detector vacuum system
  - How a mass spectrometer works
  - Helium as a trace gas
  - Description of controls
  - Tuning*
  - Calibration*
  - Rate meter reading*
  - Leak detection methods
  - Inside-out, outside-in, bomb testing and sniffer probing**

*Lecture and lab
**Semi-customized to meet class needs

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Advanced Vacuum Practice

Course Description

Advanced Vacuum Practice is a three-day course that builds on the Basic Vacuum Practice course offered by Varian. The class begins with a review of vacuum theory and moves on to calculations for building a vacuum system designed to perform at specified pressures. This includes vacuum schematics, material choices, outgassing and permeation, joining techniques, vacuum economics, pump gauging and component selection, system characterization, and software for computer-aided design and modeling.

Each day students will be using laboratory facilities to build and test designs they have chosen, and will have access to a variety of pumps and components from several manufacturers. Knowledge gained from this class will be extremely valuable for vacuum applications in the semiconductor, R&D, and manufacturing sectors.

Course Outline

Short review of vacuum principles
Vacuum system schematics
General vacuum system configuration(s)
Materials selection for use in vacuum systems
Outgassing and permeation in vacuum materials
Vacuum joint design and joining techniques
Rough vacuum pump down calculations
High vacuum pump down calculations
System hygiene, cleaning and impact on system performance
Conductance and calculations
Outgassing, permeation, and leaks
Rough and high vacuum pump selection
Component design and selection
Gauge design and selection
Vacuum economics
Characterizing vacuum systems
Measuring actual performance against manual and computer calculations

Lab Activities

Lab activities include calculating the pump-down time for mechanical pumps and measured vacuum chambers, then performing a pump down to compare the results. For the main project, the class is divided into teams and assigned a system to design and build, along with limiting parameters such as ultimate pressure, overall cost, and operating processes. Teams will then build and pump down the system, comparing the actual results to calculations.

Highly Recommended Prerequisites:
Basic Vacuum Practice
Leak Detection Applications and Techniques
(A full understanding of basic vacuum fundamentals and leak detection is assumed and will not be repeated.)

After You Finish This Course

- You will have a more thorough understanding of vacuum concepts.
- You will be able to perform calculations to determine pumping speed and pump downtime on vacuum systems.
- You will understand concepts for calculation of conductance in vacuum systems.
- You will understand concerns of outgassing and permeation of materials in vacuum systems.
- You will be able to design and build an elementary vacuum system.
- You will become familiar with computer software used to design vacuum systems.

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Specialty One-Day Courses

TriScroll and Scroll Pump Rebuilding Course

Varian now offers customers the opportunity to service and rebuild their own Varian scroll pumps. This course covers required minor and major services for both the 300 and 600 DS and 100, 300 and 600 TS model scroll pumps. This class is taught as a lecture/lab course.. (If offered at a customer's facility, proper tooling must be available or requested as part of the course.)

Course Outline

- When to service pumps
- Necessary tooling and parts
- Required precautions
- Disassembly procedures
- Cleaning methods
- Inspection process
- Reassembly, testing and conditioning

Ultra-high Vacuum Technology and Techniques

This seminar describes current methods and technologies for achieving and maintaining ultra-high vacuum. UHV chamber materials, pumping and gauging technologies for UHV systems, cleaning and handling methods, out-gassing phenomena, and coupling techniques are among many topics discussed.

Residual Gas Analyzers

This course covers one of the most useful tools for monitoring and controlling process environment in vacuum industry and R&D applications. An RGA can be used to analyze process chemistry and reagent purity, predict maintenance, and find leaks.

Course Outline

- History of mass spectrometry and terminology
- Types of RGAs and theory of operation
- Quadrapole mass filter and electron multipliers
- Differentially pumped applications for low vacuum and atmosphere systems
- Spectrum analysis and interpretation of data
- RGA selection and installation
- Applications and limitations
- Computer interface and software
- Lab activities

Gauges and Gauging

This one-day course will help the student confidently choose and use the appropriate gauge. The class covers history, use, application, and choice of vacuum gauge(s). Many other topics are discussed: process effects on various gauges, gauge accuracy, features and benefits versus cost, and the elements of gauge calibration.

At the Palo Alto facility, the course is taught in a hands-on, state-of-the-art laboratory with a specially constructed vacuum system that contains almost every gauge used today. Participants will install, operate, and observe gauges, in a manner not normally possible in working vacuum systems.

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Palo Alto and Lexington Training Schedule

October 2000– September 2001

	$995	Oct '00	Nov '00	Dec '00	Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01
Basic Vacuum Practice	Palo Alto, CA	2–4	6–8	11-13	22- 24	12-14	12-14	2-4	7-9	11-13	23-25	13-15	17-19
	Lexington, MA		10/30-11/1	11-13	22-24	12-14	12-14	2-4	7-9	11-13-	23-25	13-15	17-19

	$795	Oct '00	Nov '00	Dec '00	Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01
Leak Detection Applications and Techniques	Palo Alto, CA	5-6	9-10	14-15	25-26	15-16	15-16	5-6	10-11	14-15	26-27	16-17	20-21
	Lexington, MA	19-20	2-3	14-15	25-26	15-16	15-16	5-6	10-11	14-15	26-27	16-17	20-21

	$1495	Oct '00	Nov '00	Dec '00	Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01
Leak Detection Maintenance (Analog Electronics: 938, 94X, 95X, 960, 990 CLD)	Palo Alto, CA					5-7		23-25		18-20		20-22	
	Lexington, MA		13-15		8-10		19-21		21-23		9-11		24-26

	$995	Oct '00	Nov '00	Dec '00	Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01
Leak Detection Maintenance: 979 Model	Palo Alto, CA	26-27		7-8				26-27		21-22		23-24	
	Lexington, MA		16-17		11-12		22-23		24-25		12-13		27-28

	$1495	Oct '00	Nov '00	Dec '00	Jan '01	Feb '01	Mar '01	Apr '01	May '01	June '01	July '01	Aug '01	Sept '01
Advanced Vacuum Practices	Palo Alto, CA				10-12				23-25				12-14
	Lexington, MA						7-9				18-20		

Scroll Pumps $495		RGA $495		UHV $495		Gauges $495	
Palo Alto, CA	Feb 20	Palo Alto, CA	Feb 21	Palo Alto, CA	Feb 22	Palo Alto, CA	Feb 23
Lexington, MA	Aug 7	Lexington, MA	Aug 8	Lexington, MA	Aug 9	Lexington, MA	Aug 10

Please call for price quotes for on-site training

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Regional Courses: 2000/2001

4-Day Combined Course: Basic Vacuum Practice with Leak Detection Applications and Techniques

Year	Month	Date	City	State/ Country
2000	October	17 - 20	Fairfield	CT
2000	October	17 -20	Mississauga, ON	Canada
2000	October	24 -27	Ann Arbor	MI
2000	November	Oct 31 -Nov 3	Knoxville	TN
2000	November	7 -10	Albany	NY
2000	November	7 -10	Denver	CO
2000	November	14 -17	Indianapolis	IN
2000	November	14 -17	Houston	TX
2000	December	5 -8	Cape Canaveral	FL
2000	December	5 -8	Portland	OR
2001	January	9 -12	Phoenix	AZ
2001	January	16 -19	San Antonio	TX
2001	January	16 -19	Los Angeles	CA
2001	February	Jan 30 -Feb 2	Orlando	FL
2001	February	6 -9	Richmond	VA
2001	February	13 -16	Seattle	WA
2001	February	13 -16	Hilo	HI
2001	March	Feb 27 -Mar 2	Richardson	TX
2001	March	Feb 27 -Mar 2	Denver	CO
2001	March	Feb 27 -Mar 2	Wood Dale	IL
2001	March	6 -9	Atlanta	GA
2001	March	6 -9	Boise	ID
2001	March	13 -16	Allentown	PA
2001	March	13 -16	Salt Lake City	UT
2001	March	20 -23	Austin	TX
2001	April	3 -6	Mississauga, ON	Canada
2001	April	3 -6	Cincinnati	OH
2001	April	9 -12	San Diego	CA
2001	April	17 -20	Portland	OR
2001	April	17 -20	St. Louis	MO
2001	April	24 -27	Minneapolis	MN
2001	May	1 -4	Auburn Hills	MI
2001	May	1 -4	Cape Canaveral	FL
2001	May	15 -18	Raleigh-Durham	NC
2001	May	15 -18	Richland	WA
2001	May	21 -24	Albuquerque	NM
2001	June	5 -8	Rochester	NY
2001	June	5 -8	Phoenix	AZ
2001	June	19 -22	Arlington	TX
2001	June	19 -22	Denver	CO
2001	June	26 -29	Willow Grove	PA
2001	July	10 -13	Manassas	VA
2001	July	17 -20	Wood Dale	IL
2001	July	17 -20	Sacramento	CA
2001	July	24 -27	Seattle	WA
2001	August	July 31 -Aug 3	Pittsburg	PA
2001	August	7 -10	Cleveland	OH
2001	August	21 -24	Madison	WI
2001	August	21 -24	Greenville	SC
2001	September	11 -14	Austin	TX
2001	September	11 -14	Huntsville	AL
2001	September	18 -21	Portland	OR
2001	September	18 -21	Los Angeles	CA

Course Price: $1495 | **Call for on-site training price quotes**

Register by 2 weeks in advance of course date: courses cancel if registration is low.

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Customized On-Site Training

Course Description

One of Varian's dedicated professional trainers will present a training program at your workplace customized to meet the needs of your organization. The program will be tailored to provide the correct amount of theory and hands-on training in an appropriate amount of time. Training material from any of the following Varian courses can be combined to provide a cost-effective on-site training solution.

Varian's Standard Courses

- Basic Vacuum Practice
- Leak Detection Applications & Techniques
- Advanced Vacuum Practice
- Ultra-high Vacuum Technology and Techniques
- Residual Gas Analyzers
- Gauges and Gauging
- Scroll Pump Rebuilding
- Leak Detection Maintenance

Training Equipment

Training equipment is available from Varian at additional charge, including:

- Turbo-pumped high vacuum system
- Varian Helium Mass Spectrometer Leak Detectors
- Ultra-high vacuum system (dry mechanical, turbomelecular and ion pumps)
- Residual Gas Analyzer (differentially-pumped, atmospheric sampling)
- Specially constructed vacuum system that contains almost every gauging technology used today in modern vacuum systems
- Other equipment available upon request

On-Site Training Charges

(Per instructor, per 8-hour day during regular business hours. Additional charge for off-shift and weekend training)

0-100 miles (from Palo Alto, CA or Lexington, MA)		**101-400 miles (from Palo Alto, CA or Lexington, MA)**		**401-1000 miles (from Palo Alto, CA or Lexington, MA)**		**Over 1000 miles (from Palo Alto, CA or Lexington, MA)**	
1 day training:	$3,000	1 day training:	$3,500	1 day training:	$4,000	1 day training:	$4,500
2 day training:	$5,500	2 day training:	$6,000	2 day training:	$6,500	2 day training:	$7,000
3 day training:	$8,000	3 day training:	$8,500	3 day training:	$9,000	3 day training:	$9,500
4 day training:	$10,500	4 day training:	$11,000	4 day training:	$11,500	4 day training:	$12,000

A purchase order, credit card or check is required to hold dates for on-site training.
Varian's Training cancellation policy detailed in the registration form also applies to on-site training.

For additional information, or to set up an on-site training that meets your specific training requirements, call 1-800-882-7426, option 3

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Research paper

BEST PAPER AWARD ON BEHALF OF
MICROELECTRONICS JOURNAL FOR THE CAS'94
CONFERENCE

Design of a silicon microsensor array device for gas analysis

Florin Udrea[1] and Julian W. Gardner

Department of Engineering, University of Warwick, Coventry CV4 7AL, UK

This paper describes the design of a silicon-based microsensor array for application in gas or odour monitoring. Individual sensor cells consist of both lateral and vertical electrode pairs to measure film conductance and/or capacitance. The fabrication process involves standard silicon technologies to integrate a platinum or nickel-iron heater below the sensor cells. A simulation of the device gives a thermal response time of only 60 ms and an ultra low power loss of about 50 mW at 400°C per sensor. This compares well with experimental values observed on a similar device. The process technology is suitable for both the deposition of organic materials (e.g. conducting polymers) and inorganic materials (e.g. semiconducting oxides). A scheme of the transducer interface circuitry is also provided, and could be used in a portable battery-powered instrument. Copyright © 1996 Elsevier Science Ltd.

1. Introduction

The development of an integrated silicon sensor array capable of discriminating between simple and complex odours has received considerable interest in recent years [1]. Some advantages of silicon sensors are that they offer the low power consumption necessary for portable devices, possess a fast thermal response time, can be made at low cost and permit the integration of associated electronics. Individual silicon sensor devices with a thin diaphragm featuring very low power consumption have been reported previously [2–4]. Compared with individual sensor devices a sensor array has the advantage of improved gas selectivity, lower noise and reduced effect of poisoning through superior data processing methods (e.g. adaptive neural networks).

This paper describes the theoretical design of such a microsensor array design which not only features a very low power consumption but also allows for great flexibility in the choice of the gas-sensitive material, such as low temperature organic materials (e.g. conducting polymers [5]) or high temperature semiconducting oxides [6].

[1]F. Udrea is now with the Engineering Department, University of Cambridge, Cambridge CB2 1PZ, UK.

2. Device description

2.1 Cross-section

A schematic cross-section of one cell of the silicon array device in which the active film is thermally isolated on a thin diaphragm is shown in Fig. 1. The bulk silicon is removed using an anisotropic back-etching process (e.g. KOH) to leave the thin diaphragm. The sensing cell is divided into two sensors. The first sensor comprises a pair of interdigital co-planar electrodes on top of which the sensing material is deposited, and can operate in a trans-conductive mode (termed lateral sensor). The second sensor is a sandwich structure of two electrodes and a thin gas-sensitive layer which can operate both in the capacitive and conductive mode (termed vertical sensor), thus measuring the change in the electrical conductivity and dielectric constant in the presence of gases. The integration of both geometries in the same device (i.e. lateral and vertical) gives a great flexibility in the sensor response to various gases and also helps to characterize fully the nature of the interaction between the sensing material and a given gas (e.g. reaction kinetics of the change in resistivity and dielectric constant). The heater could be placed on the surface and surround the sensitive area [7], however a vertical arrangement [2–4] as shown in Fig. 1 is preferable because it minimizes the power consumption and size of active area. The heater is sandwiched between two layers to protect it from atmospheric contamination.

2.2 Thermal losses and heater resistance

There are three main contributions to the total thermal loss: first, a thermal loss due to conduction through the diaphragm H_m; second, a loss to the surrounding air due to the thermal convection and conduction H_a; and finally a loss due to radiation H_r. The total losses are determined by the geometric size (thickness h, membrane length l and active area dimension a), the specific thermal conductivity σ of the membrane material and the temperature difference ΔT. According to Dibbern [2] the total power losses can be expressed as:

$$H_t \approx H_m + H_a \approx \left[\frac{2\pi \cdot \sigma \cdot h}{\ln(l/a)} + \alpha a^2\right]\Delta T \qquad (1)$$

where the first term is due to conduction losses while the second expresses the convection losses. For a first order approximation the radiation losses and the dependence of the convection losses with ΔT^2 at high temperatures have been neglected. In eq. (1) $\alpha \approx 0.35\,\mathrm{mW\,mm^{-2}\,K^{-1}}$, $l/a = 3$, $h = 10\,\mu\mathrm{m}$ and $\sigma \approx 2.5\,\mathrm{W\,m^{-1}\,K^{-1}}$ for glasses or oxynitrides; $h = 1\,\mu\mathrm{m}$ and $\sigma \approx 28\,\mathrm{W\,m^{-1}\,K^{-1}}$ for silicon nitride.

The heater resistance R is approximately given by:

$$R \approx \rho \frac{L}{w \cdot t} = N \cdot r \qquad (2)$$

where ρ is the resistivity of the heater material, L is the length of the heater, t is the thickness of the heater layer, w is the width of one line of heater, r is the resistance per square and N is the square number. The power P_h developed by the heater is $P_h = V_h^2/R$. For a value for P_h of 150 mW and a heater voltage V_h of 5 V the resistance should be about 165 Ω. Please note that the value of $P_h = 150\,\mathrm{mW}$ is for two sensors at 600°C which is equivalent with a power consumption of 50 mW per sensor at 400°C.

Several materials can be used to make the heater, such as polysilicon, platinum or NiFe. The material selected by Dibbern [2] was NiFe (81:19) permalloy, which offers a high stability

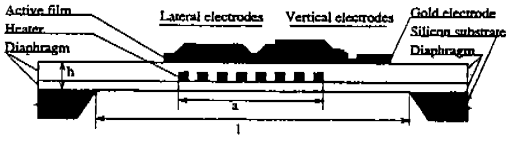


Fig. 1. Schematic cross-section of one sensing cell of a silicon microsensor array device.

against electromigration and tolerates a current density up to 10^{11} A/m^2. The specific resistivity at 600°C is about 7.5×10^{-7} Ωm. Permalloy has a significant temperature coefficient of resistance (TCR) which enables temperature measurement by the heater itself, thus eliminating the need for an additional temperature sensor. Another commonly used material for the heater is platinum. Platinum is easy to deposit and has a linear and stable TCR at high temperatures. The compromise between a relatively large sensitive area and a small active area to minimize the losses leads to a value of a of 0.5 mm (a is the dimension for the square active area, as shown in Fig. 1). It should be noted that although the resolution of microlithography permits much smaller values of a, a very small sensitive area will adversely affect the robustness of the sensor due to easier contamination. Moreover, for conducting polymers, the reduction of the electrode area is limited by the ability of the potentiostat to grow polymers reliably with minute currents [8]. For $a = 0.5$ mm from eq. (1), one can obtain the total thermal losses in the device: $H_t = 135$ mW at 600°C. The electric power will be slightly greater than the estimated thermal losses. This is the reason that we have already chosen $P_h = 150$ mW. The shape of the heater is given in Fig. 2 (top). There are three basic requirements for the heater geometrical design: first, that the heater electrode should cover uniformly the sensing area (to avoid any gradients in the temperature); second, that the heater resistance is higher enough at those dimensions to provide a driving voltage to be about 5 V at the required operating temperature; and third, that the heater dimensions should be small (heater area, heater thickness) to reduce the radiation losses. The following dimensions for the heater have been chosen for our particular design and in accordance with our laboratory facilities [9]: width of the heater truck $w = 40\,\mu$m, length of the heater truck $L = 480\,\mu$m, the gap between two trucks $g = 25\,\mu$m, number of trucks $n = 8$

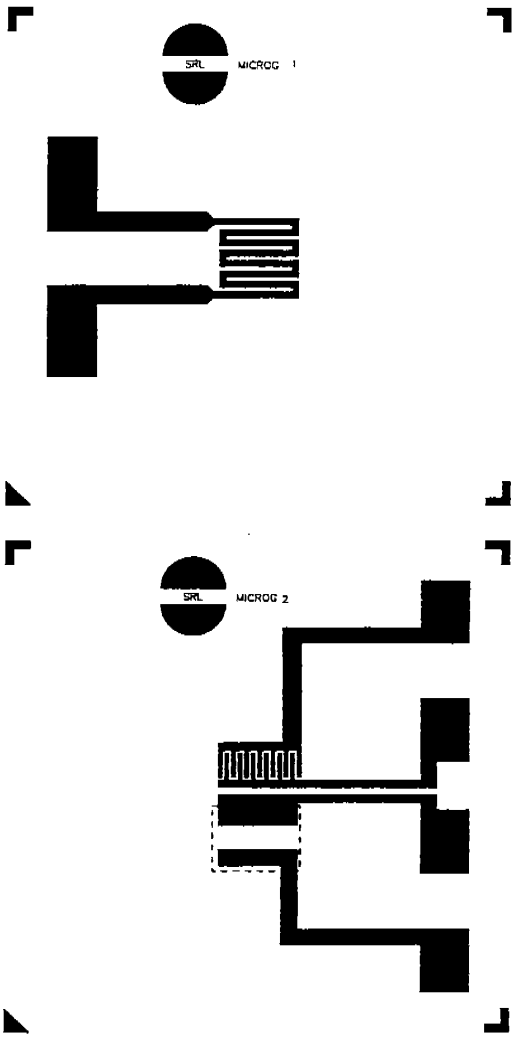


Fig. 2. Mask patterns for the cell heater (top) and sensing electrodes (bottom). The top electrode location is represented by a dotted line.

and the thickness of the heater layer $t = 0.5\,\mu$m. The square resistance has been evaluated at $r = 1.5\,\Omega$ per square, and the numbers of squares $N \approx 100$.

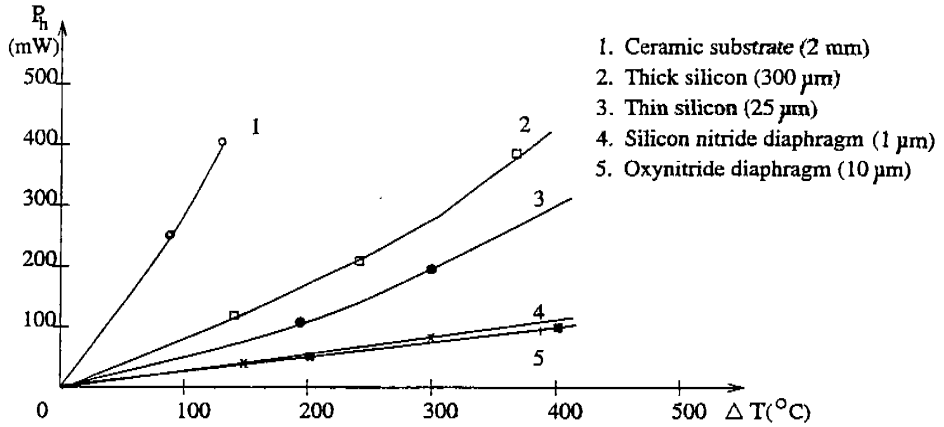


Fig. 3. Theoretical heater power consumption for oxynitride and silicon nitride membranes and test measurements for ceramic thick silicon and thin silicon substrates from [10].

Figure 3 shows the theoretical heater power consumption P_h against the operating temperature relative to ambient, ΔT. The theoretical power losses estimated for the oxynitride and silicon nitride membranes are considerably lower than the experimental values reported for ceramic, thick silicon and thin silicon [10].

A two-dimensional numerical simulation using the simulator TMA MEDICI [11] of the lattice temperature distribution in the sensor cell was performed. The bridge structure shown in Fig. 1 was imported in MEDICI and simulated using a non-uniform grid with high density in the diaphragm area. The lattice heat equation available in MEDICI accounts for the conduction losses in the diaphragm and outside the diaphragm frame. Simulations have been performed on both silicon nitride diaphragm (thickness = 1 μm) and oxynitride (thickness = 10 μm). The results (Fig. 4) show that the temperature is uniformly distributed in the active area and decreases abruptly outside the diaphragm area. This is consistent with the temperature measurements of the silicon substrate and diaphragm reported by Krebs and Grisel [4]. Low temperatures outside the diaphragm area suggest that theoretically it is possible to integrate an electronic transducer in the same chip with the sensing device.

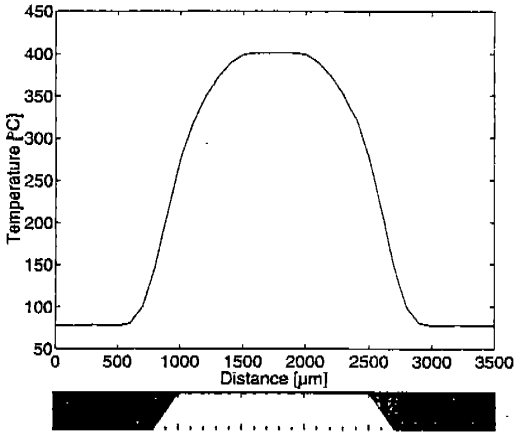


Fig. 4. Theoretical temperature distribution in the cross-section of the sensor cell. The power consumption in this case is nominally 100 mW per cell (50 mW per sensor). Data extracted from numerical simulations using MEDICI.

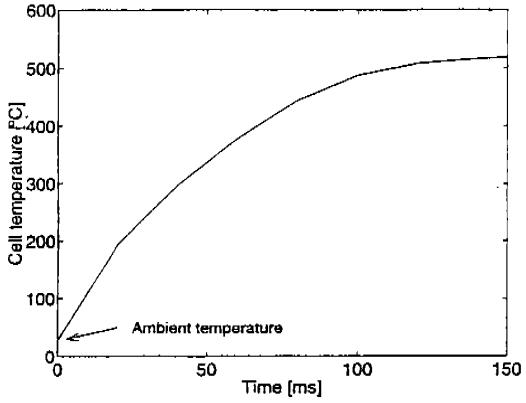


Fig. 5. Thermal response of the diaphragm of the sensor cell. The heater driving voltage rises from 0 to 4 V in 1 μs.

The thermal response time to a rise in the electric voltage applied across the heater electrodes determines the maximum rate at which temperature cycles can be run. It was mentioned that one of the advantages of the silicon sensors is their fast thermal response. In Fig. 5 a numerical simulation of the thermal response for an increase in the heater voltage from 0 to 4 V in 1 μs is shown. The thermal response time is very low and has a value of around 60 ms.

2.3 The base-line resistance of the sensitive element

The base-line resistance is defined as the resistance in air under ambient conditions. For the vertical structure, the capacitance C_{01} and the resistance R_{01} are given by:

$$C_{01} = \frac{\varepsilon_1 S_1}{h_1}; \quad R_{01} = \frac{\rho_1 h_1}{S_1} \tag{3}$$

where ρ_1, ε_1, h_1 and S_1 are the resistivity, the dielectric constant, the thickness and the area of the sensing material, respectively. For the lateral sensor, the base-line resistance is written as [9]:

$$R_{02} = \frac{\pi \cdot \rho_2}{l_2} \cdot \frac{1}{\ln\left(\frac{2h_2}{w_2} + \sqrt{\left(\frac{2h_2}{w_2}\right)^2 + 1}\right)} \tag{4}$$

where ρ_2 and h_2 are the resistivity and the thickness of the planar cell sensing material respectively, l_2 is the total length of one electrode and w_2 is the gap between electrodes. For the design shown in Fig. 2 (bottom), $h_1 = 1\,\mu$m, $S_1 = 480\,\mu\text{m} \times 160\,\mu$m, $h_2 = 1\,\mu$m, $w_2 = 15\,\mu$m, $l_2 = 2.4$ mm. ρ_1 and ρ_2 vary for various sensing materials (metal oxides, polymers) between 10^{-2} and $10^3\,\Omega$m.

3. Fabrication process

The technological process proposed for the fabrication of these devices uses eight photographic masks. In the case of tin oxide deposition: Mask1 — photolithographic patterning of the heater (Fig. 2 top); Mask2 — photolithographic patterning of the sensing element electrodes (Fig. 2 bottom); Mask3 — tin oxide deposition; Mask4 — top porous thin electrode deposition (in the sandwich cell), Mask5 — diaphragm formation, anisotropic back etching of silicon using a silicon oxide layer as a stop and KOH as etchant; Mask6 — photolithographic opening of windows in diaphragm material (in the outer frame) to form contacts with the top electrodes; Mask 7 — photolithographic opening of windows in diaphragm material (in the outer frame) to form contacts with the bottom heater layer; Mask8 — to increase the metal thickness in the pad zones. For more details of a possible fabrication process see [12].

For polymer films that react with gases at temperatures less than 120°C, a simplified process using only five masks (masks 3, 5 and 7 are removed) can be employed. Although the use of polymers as the active material reduces the number of masks and eliminates the need for a thin suspended diaphragm structure, special

deposition equipment is needed to grow the polymer on chip [8]. Presently, polymer research is being directed towards the control of the electrical properties of conductive polymers, in particular the base-line resistivity, the drift in time, and temperature [13].

3.1 Diaphragm film deposition

The most important part of a silicon array device which is required to operate at high temperature is the diaphragm. The material and method of deposition determine clearly the mechanical stability, stress and low power consumption of the diaphragm. Oxynitrides or a sandwich combination between plasma oxide and plasma nitride (to compensate for the stresses) seem to match our requirements [2]. Another solution is to use boron silicate glasses which offer a very low specific conductivity [9]. The thickness of the diaphragm is chosen to be $h = 10\,\mu m$, oxynitride, which results in power losses of only 50 mW per sensor at 400°C. If the mechanical problems can be overcome (e.g. by reducing the intrinsic stress during deposition) the thickness of the diaphragm can be reduced and thus silicon nitride (low-stress LPCVD deposition [12]) or amorphous carbon-type materials could be used. However, it is important to note that the thermal conductivity of silicon oxides is an order of magnitude lower than that of silicon nitrides, therefore in order to obtain a good thermal insulation, very thin diaphragms are required (e.g. less than 1 μm).

4. Transducer and interface circuitry

A block scheme of the interface circuitry and the transducer is shown in Fig. 6. The transducer comprises two basic circuits, a 'delta' circuit designated to give a linear output response with the change in conductance ($\delta = (G_x - G)/G_0 = R_x/(R_0 - R_x)$, where G_0 and R_0 are the base-line conductance and resistance) and a bridge circuit which can measure both the change in resistance and capacitance due to the presence of gases. The basic diagrams of the delta and bridge circuits are shown in Fig. 7. In the case of the delta circuit, the drift of the base-line resistance is compensated by adjusting the resistance R_0 so that the output voltage is virtually equal to zero. The output voltage which is linearly proportional with the change in the conductance due to the presence of gases can be amplified using the feedback resistance of the second operational amplifier, R_2.

$$\delta = \frac{R_0}{R_2}\,\frac{V_0}{V_{REF}} \tag{5}$$

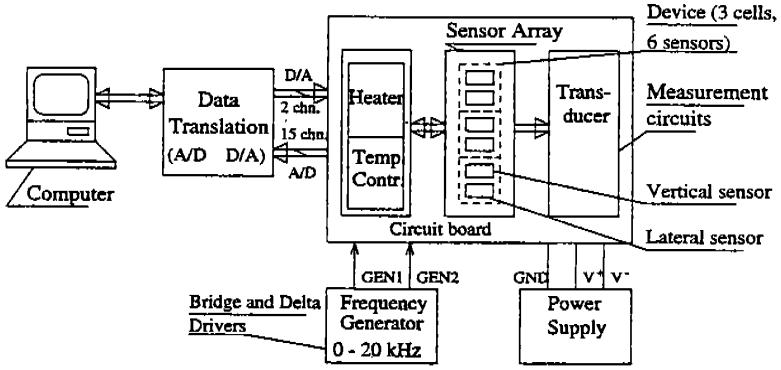


Fig. 6. Schematic diagram of the transducer and interface circuitry.

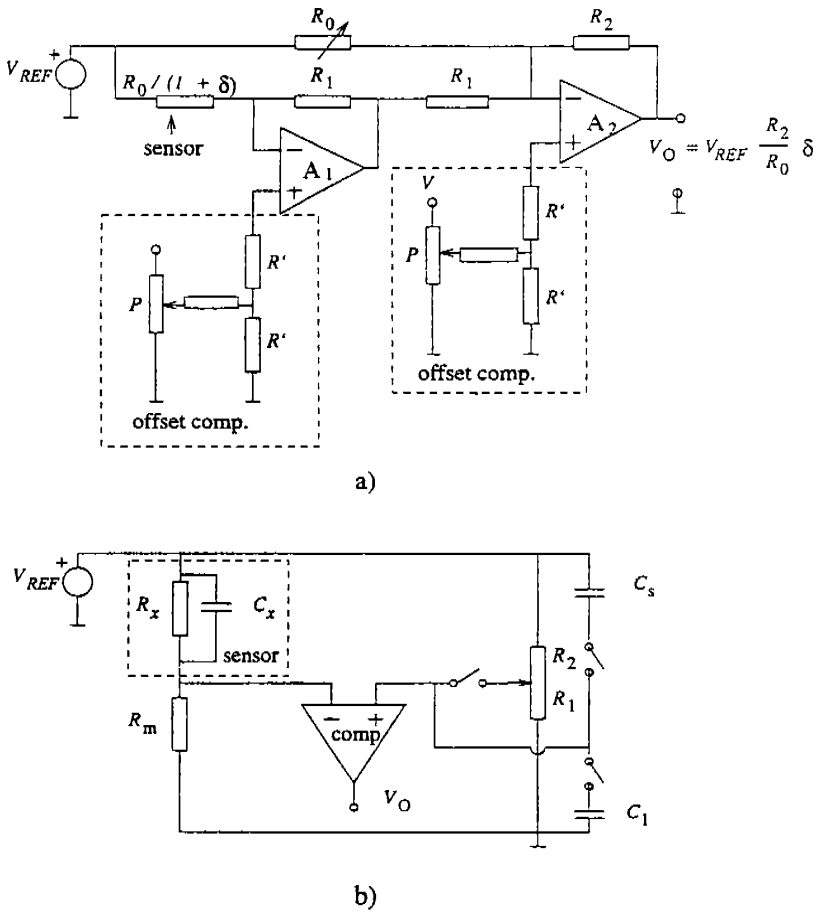


Fig. 7. Schematic electrical diagrams of (a) the delta circuit and (b) the bridge circuit.

In the case of the bridge circuit, the base-line resistance drift is eliminated by balancing the bridge in clean air. The change in the resistance is then given by:

$$\delta = \frac{1}{\beta} \cdot \frac{V_0}{(\beta - 1)V_{\mathrm{REF}} - V_0} \tag{6}$$

where $\beta = R_1/(R_1 + R_2) = R_m/(R_0 + R_m)$.

The absolute value of the capacitance in the presence of gases can be obtained by using step by step measurement to separate the sensor resistive component. Initially the bridge is balanced at low frequency from R_1 and R_2 and at high frequency from C_s with C_1 disconnected. Subsequently, connecting C_1 and disconnecting the potentiometer $R_{1,2}$ one can find out the value of the sensor capacitance C_x as:

$$C_x \simeq \frac{R_1 C_1}{R_m} \frac{V_0}{V_{REF} - V_0} \quad (7)$$

and the change in capacitance as: $\delta_c = (C_x - C_0)/C_0$.

A driving circuit for the heater and a temperature controller integrated with the computer are shown schematically in Fig. 6. The driving circuit consists of a constant current source which receives the input data from the computer. The temperature is measured by detecting the variation of the heater resistance and can be accurately adjusted through a high speed 12-bit ADC card (e.g. Data Translation DT 2811).

5. Results and further work

Figure 8 shows a photograph of the prototype silicon device fabricated at Warwick University in 1992 [9] consisting of three sensor cells each with lateral and vertical sensing electrodes. The structure permits the simultaneous measurement of film conductance and capacitance in different directions. For this particular device polypyrrole was used as a sensitive material. The polypyrrole layer was grown onto the electrical electrodes using a new electro-chemical method [8]. A set of more advanced fabricated silicon sensor array devices is shown in Figs. 9a and 9b.

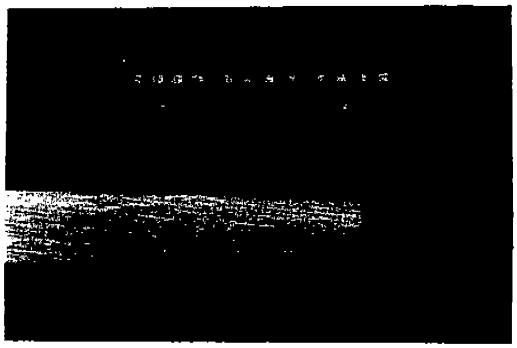
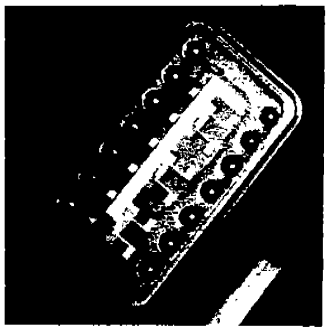


Fig. 8. A prototype silicon sensor array device for gas analysis.

(a)



(b)

Fig. 9. Photographs of (a) the cell structure of a 0.5 μm Si_3N_4 diaphragm with integrated platinum heater and interdigitated electrodes and (b) the array device mounted on a 14 pin 0.1 inch d.i.l. package [12]. The large truck shows a common for the six sensor inputs. The three heaters are not commoned.

These devices are comprised of six sensors (two per cell) with an ultra thin Si_3N_4 diaphragm deposited by a low stress LPCVD technique at the University of Neuchatel [12]. The experimental results of the power losses per sensor agree well with the theoretical predictions (Fig. 10). Full experimental results on these sensor array devices, which include measurements of the time constants and the sensor response to various solvents such as toluene, *n*-propanol, methanol, etc. have been reported elsewhere [12]. The measurements presented in [12] discuss doped tin oxide as the sensing material. Work on sensor arrays using polymers and sensor arrays with mixed conductive polymers

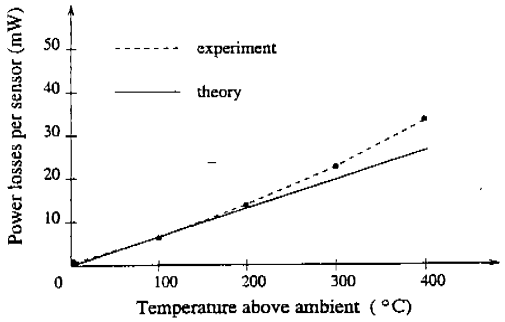


Fig. 10. Theoretical and experimental results of power losses per sensor. The dotted line shows the actual behaviour of a Si_3N_4 array device with a ultra thin diaphragm of 500 nm (from [12]).

and semiconducting oxides is presently under way in the Sensors Research Laboratory, University of Warwick, and will be reported soon.

6. Conclusions

This paper describes the design of a silicon microsensor array device suitable for application in gas or odour monitoring. The theoretical values of the heater resistance, cell power consumption and thermal response agree well with experimental values. The ultra low power consumption of about 50 mW per sensor at 400°C and ultra fast thermal response time of about 60 ms make this an attractive device for practical use. For example, the device temperature could be modulated sinusoidally, to obtain rapidly the characteristic response-temperature curve for target gases. Dynamic models could then be used to enhance the specificity of this device over conventional gas sensors which operate at a constant temperature. Moreover, an array with some replicated sensors could be used to reduce noise and remove common-mode effects in bridge arrangements [14].

Acknowledgement

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NAMAS AND TAYLOR HOBSON.....

Since August 1995 National Accreditation of Measurement and Sampling (NAMAS) has been operated by the United Kingdom Accreditation Service (UKAS) which fulfils the same function as the former National Measurement Accreditation Service.

This function is to satisfy the need for an internationally recognised national organisation to provide industry with the means to obtain "traceability" of measurements to national standards via accredited laboratories.

Certificates from accredited laboratories are accepted in an ever increasing number of countries throughout the world, as providing the traceability of measurement required by quality systems standards.

NAMAS was established in 1985 and incorporated the British Calibration Service (BCS), itself founded in 1966.

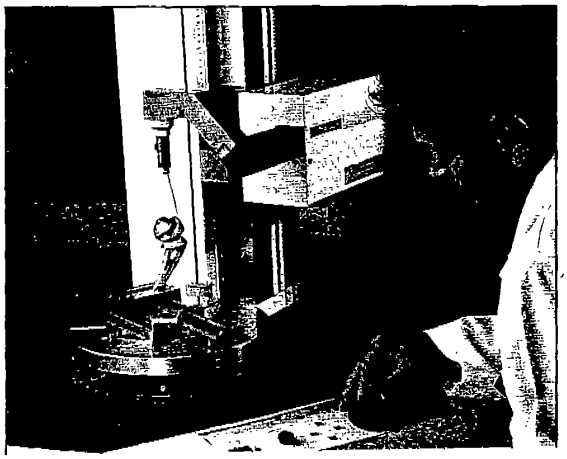
The Laboratory

For more than 20 years the Taylor Hobson Measurement Services Department has provided an accredited calibration and measurement service for industry and first achieved accreditation in 1970.

Within its NAMAS schedules of accreditation the laboratory is able to offer exceptional accuracies of measurement. These schedules cover both calibration of artefacts and small instruments within the laboratory (Category 0) and large instruments on customers' sites (Category 1). This enables customers to minimise their own uncertainties of measurement and provide traceability to National Standards as required by ISO 9000 registered quality systems.

The calibration and measurements service is designed to give metrology support at all stages of the production process, from research and development to production batch measurement.

A NAMAS certificate can actually improve measurement capability by quantifying the errors in measuring instruments. These errors can subsequently be taken account of and the measurement error corrected, thus increasing measuring accuracy.



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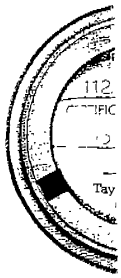

- United Kingdom (NAMAS)
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- The Netherlands (RvA)
- New Zealand (TELARC)
- Sweden (SWEDAC)
- Switzerland (SAS)
- Denmark (DANAK)
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- Belgium (OBE - BKO)

A mutual recognition agreement exists between NAMAS and the national accreditation schemes of the countries listed on this page. These agreements are under the auspices of either the European Co-operation on Accreditation of Laboratories (EAL) or as individual bilateral agreements. In an age where many projects are multinational, this arrangement gives confidence and formal assurance to companies that both they, and their international partners, are working to comparable standards of measurement.

NAMAS also has mutual recognition agreements with:

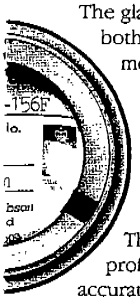
Spain (ENAC)
South Africa (SANCS)
Norway (NA)
Ireland (INAB)

TH/USA Nist Traceability

The result of a calibration exercise between the Taylor Hobson Laboratory and the National Institute of Science and Technology (USA), is that traceability may now be demonstrated between the two parties. Documentation is included with each Taylor Hobson NAMAS certificate which enables the user to show the same traceability. Formal agreement between NAMAS and NIST is expected to be ratified by late 1998.

. NAMAS ACCREDITED CAPABILITY.....

Roundness



The glass hemisphere is a high precision standard used to both calibrate and evaluate the performance of roundness measuring instruments.

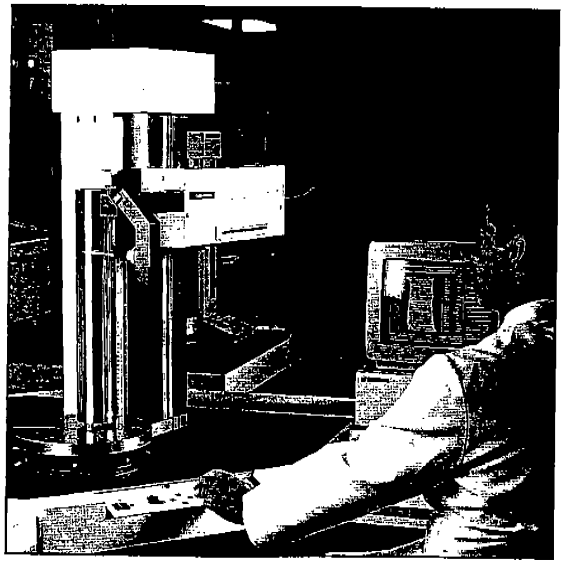
By using exclusive measurement techniques, the NAMAS laboratory calibrates the hemisphere to a resolution of 1 nanometre, with an uncertainty of measurement of 5 nanometres.

The resulting certificate includes a polar plot of the profile of the measured plane, which allows the user to accurately ascertain any errors in their own system.

Measurement	Best Capability
Roundness of Standards and workpieces	±0. 005 μm
Cylindrical Magnification test specimens	±0.05 μm
Straightness Parallelism Squareness	Dependent on precision of item
Diameter Length	±0.5 μm (20μin) ±0.5 μm (20μin)
Roundness instruments	Dependent on quality and performance

Straightness

Assessment of the accuracy of a straightness and cylindricity measuring instrument can be achieved at any time by measuring a precision cylinder. The result can then be compared with the calibrated profile on the NAMAS Certificate.



Surface Texture

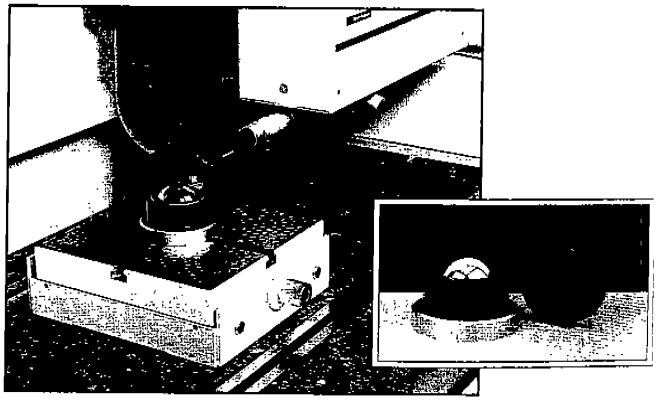
The NAMAS laboratory is able to measure all of the parameters associated with surface texture, including German and French derivatives.

Roughness standards are calibrated to an uncertainty of Ra which is the lowest currently available from any laboratory covered by the United Kingdom's Accreditation Service.

The tungsten carbide calibration ball is used to calibrate the Form Talysurf Series range of instruments. Its radius, roundness and surface texture are each calibrated to provide a high precision multi-purpose standard.

The ball may be used to calibrate the instrument, or as a "confidence gauge", to ensure its accuracy is maintained.

Measurement	Best Capability
Surface texture standards (Ra) Other parameters available)	±(2% of 0.004μm)
Surface texture of workpieces and components (Ra) Other parameters available)	±3% of measured value per track
Radius (derived)	±0.4μm



Diameter and Length

The laboratory is currently accreditated for the calibration of spheres, plugs, rings and length bars. Temperature corrected measuring techniques are used in conjunction with sophisticated control software to achieve uncertainties down to ±0.5μm.

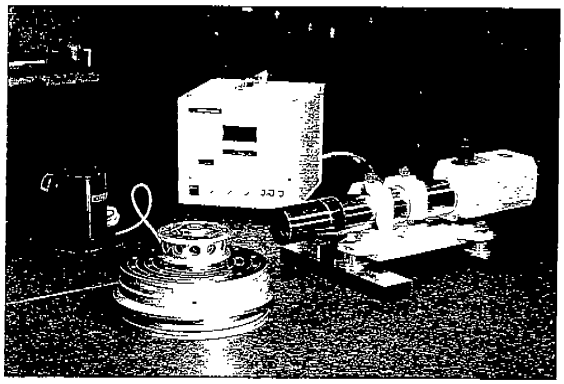
Measurement	Best Capability
Spheres (diameter)	±0.5μm
Spheres (radius)	±0.4μm
Plug Gauges	±0.5μm
Ring Gauges	±0.8μm
Length Bars	±0.5μm

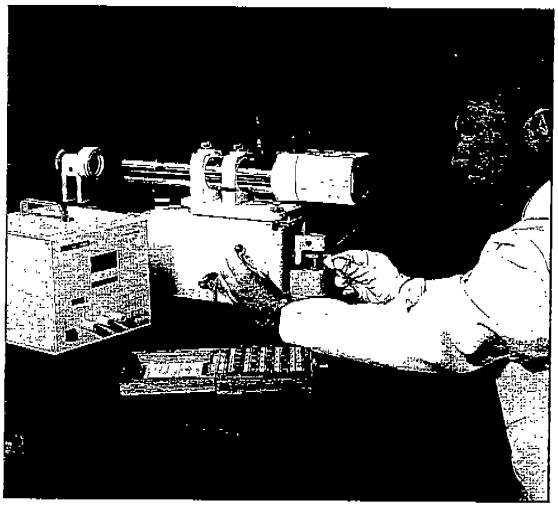
.. NAMAS ACCREDITED CAPABILITY.....

Polygons and Prisms

The basic methods employed for angle measurement are either the accurate division of a circle, by using a high precision index table, or the generation of a known angle by means of a precision sine bar (Angle generator).

A precision index table is used in conjunction with an autocollimator to calibrate a polygon. Any errors found in the polygon are tabulated on the NAMAS certificate. By taking these errors into account during its use, a higher accuracy of measurement can be achieved.





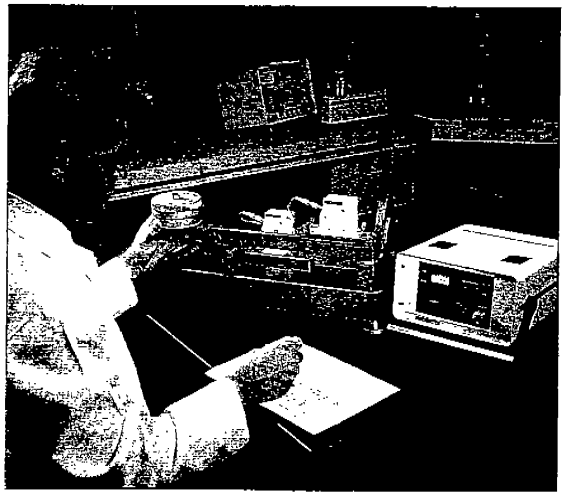
Autocollimators

A small angle generator is normally used with traceable gauge blocks to calibrate an autocollimator. Both progressive and periodic errors are measured and certified. Knowledge of these errors enables more precise use of the instrument by the operator.

Measurement	Best capability
Angle gauges, Polygons, Prisms & Optical squares	±1 arc second
Autocollimators	±0.5 arc second
Clinometers, Spirit and electronic levels	Dependent on quality, sensitivity and overall performance
Rotary Tables	±1.0 arc second

Clinometers and Levels

Block levels, clinometers, and electronic levels are calibrated by use of lever techniques. Here a Talyvel 4 Electronic Level is calibrated using a Taylor Hobson small angle generator. The user benefits from the ability to compensate for known errors when using the instrument.



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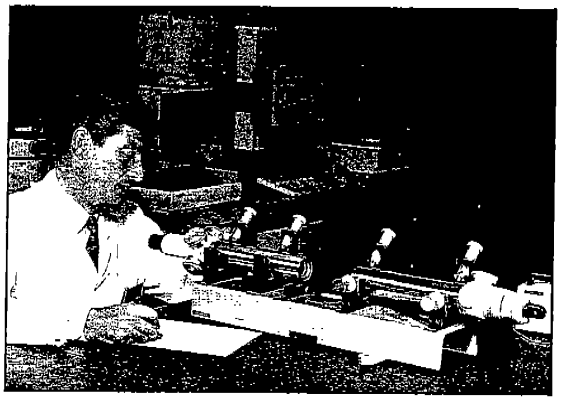
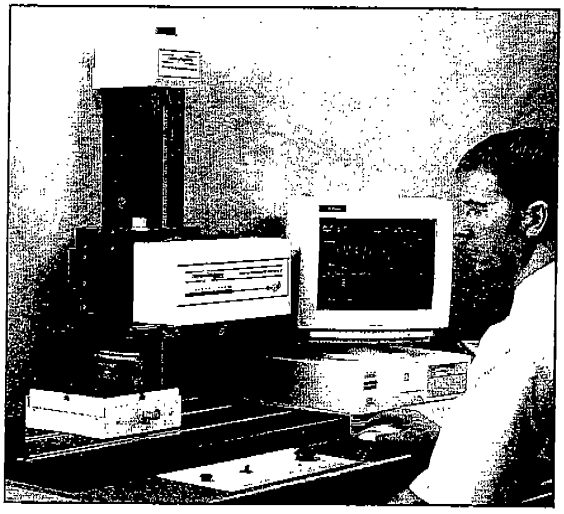
Telescopes

The line of sight and displacement errors of a Micro Alignment Telescope are assessed by viewing into a variable focus collimator. Again, any deviations are recorded on the NAMAS certificate, providing the means for more accurate measurement.

Measurement	Best Capability
Alignment telescopes, Targets & collimators	Dependent on quality and overall performance (typically ±0.25μm)





CATEGORY 1:
On-site Calibration

In addition to its range of accredited calibrations made within the permanent laboratory (category O), Taylor Hobson also has Category 1 Accreditation, which allows our approved operators to undertake calibration and/or verification of the Taylor Hobson ranges of measuring instruments and machine tools on customers premises. The uncertainties for these types of calibrations are environment dependent, which is continually monitored for the duration of the calibration and also the equipment stabilisation period beforehand.

Measurement	Best Capability
Straightness on slides	±0.15μm
Squareness on slides	±1 arc second
Roundness	±0.05μm

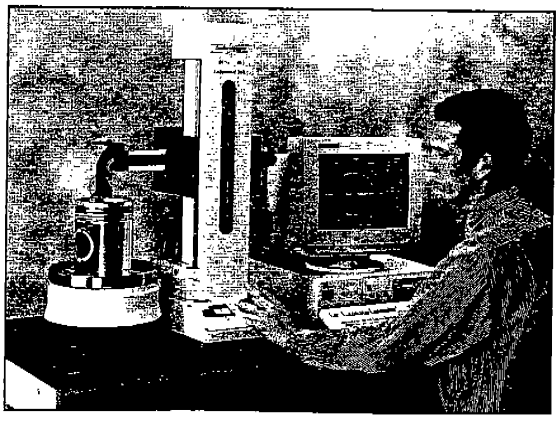
MEASUREMENT SERVICES

In addition to NAMAS calibration, Taylor Hobson also offers a wide range of measurement and inspection services.

This comprehensive service extends from bench inspection to co-ordinate measuring machine work, from micro surface evaluation to civil engineering applications.

The extensive range of measuring equipment manufactured by, or used within Taylor Hobson, is available for use by the laboratory staff.

Diverse sectors of industry and technical establishments use this service to help solve their measurement problems.



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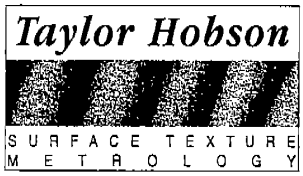

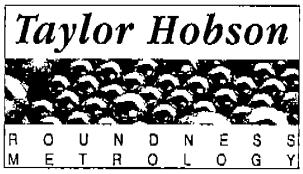

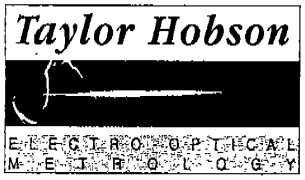

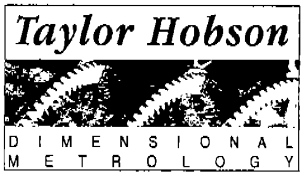

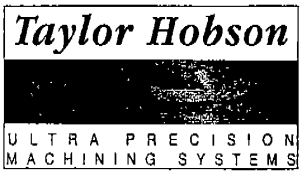

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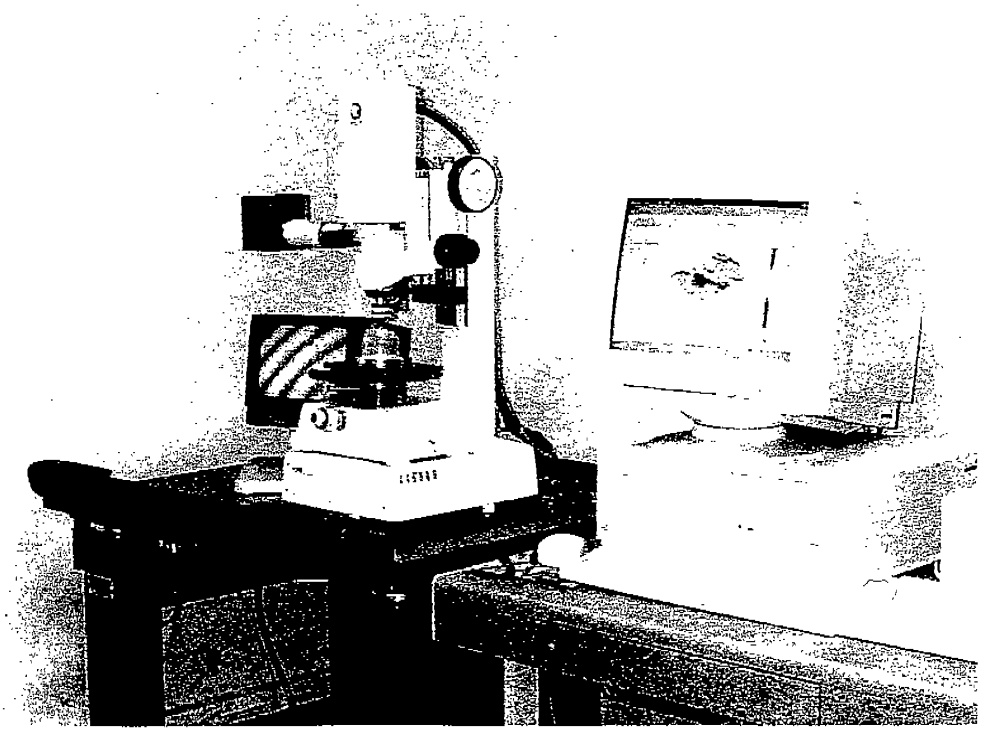
		RESPONSIBLE ENGINEER
		DEPARTMENT MANAGER



Measuring Instrument.

Weight.	1120Kg
Sizes.	Width 1284 x Depth 884 x Height 1800

Granite Table & Frame.

Size;	1200 x 800 x 150mm.
Height of work platform;	1030mm
Frame;	Fabricated steel frame with detachable panels for accesses. Controller, EIM, and Pneumatics housed within the frame.
Anti-Vibration Mounts.	Pneumatic mounts type SLM-12. 20-80 PSI air pressure required. Isolation 10 Hz

'X' stage.

Type;	Aerotech ATS8000 complete with cable guide, linear motor and grating.
Travel;	400mm (datalogging 310mm).
Data spacing;	Below 28.8mm 0.24μm/above 28.8mm 2.64μm
Dynamic flatness;	0.5μm/300mm
Dynamic Straightness;	2.0μm/300mm
Holding force (power on);	130N
Traverse speeds;	0.5, 1.0, 2.0, 5mm/sec
Grating resolution;	0.02μm
Position accuracy;	+/- 10μm.
Repetability;	+/- 1μm
Dynamic noise ;	80nm Prq on plano surface.
Payload;	10kg
Cable lengths;	5M

Component Worktable.

Worktable diameter;	300mm.
Worktable rotation;	360° Manual operation. Skirt marked every 10°
Levelling Stage;	Pitch +/- 1.5mm, Yaw +/-1.5mm. Manual operation.
'Y' axis Stage;	+/- 5mm Manual Operation

'Z' Axis & Gantry.

'Z' Axis Movement;	0-180mm above the worktable.
Movement Modes;	Selectable via the computer, Continuous, positional or follow. Manually via the joystick box.
Alignment of 'Z' axis in the 'X' direrction;	1μm/80mm
Alignment of 'Z' axis in the 'Y' direrction;	3μm/80mm
Traverse speed;	0.25, 0.5, 1.0, 2.5, 5.0, 8.0mm/sec (Selectable).
Position accuracy;	+/- 50μm.

Gauging.

Laser;	2mw Helium Neon. Class 111A
Interferometer Resolution;	9.88nm
Gauging Range;	165.885mm Maximum.
Gauging Force;	1-2gf.
Gauge Pressure;	40 PSI.
Follow gauge range;	+/-0.5mm
Follow gauge type;	Optical Shutter.

Maximum Slope;	45° From the Horizontal.

Software.

Computer;	Hewlett Packard VL5/133 with 14" Monitor.
Surface Analysis options;	None.
Form Analysis options;	Display and analyse form to a datum. Display and analyse form to a L.S. line. Display and analyse form to a Minimum zone. Display and analyse form to a L.S. arc. (auto) Display and analyse form to a L.S. arc (specified Radius). Display and analyse form to Specified Aspheric Coeficients.(Including base curve fit) Display and analyse form to Specified Ellipse or Hyperbola.Display and analyse form to Specified Aspheric Coeficients.(Including base curve fit) Display and analyse form to Specified Ellipse or Hyperbola. Best fit radius computation on aspheric forms. filtered profiles on aspheric forms. Power density spectrum display

Styli.

Ball Tipped Styli;	Ø1mm Ruby.
Diamond Tipped Styli;	10μm 60° conisphere

System accuracies.

Form.	
Best fit straight line;	0.5μm over 300mm (0.8mm cut-off, Gaussian filter)
Best fit circular arc;	1.0μm over 300mm (0.8mm cut-off, Gaussian filter)
Inclanation.	
To best fit straight line	
Range;	+/- 45°
Accuracy;	less than 0.5mins.
Radius.	
2 to 1000mm	0.02 to 0.2% of nominal.

System Requirements.

Supply Voltage.;	230 volts, 50 Hz or 110 volts, 60 Hz single phase three wire AC system including seperate earth (ground) Instrument Factory configured.
power Consumption;	350 VA.
Laser Clasification;	Class 2

This equipment is intended for installation category (overvoltage category) II, in accordance with IEC 1010 (1990) and EN 61010-1 (1993).

Air Supply;	
Pressure;	4.3 to 10 bar gauge.
Flow rate;	78.6 litres/min. (2.77 S.C.F.M)
Moisture Content;	Dewpoint (Pressure) at -20 °C
Maximum oil Content.	25 mg/m^3
Solid Partical Content.	5 mg/m^3
Maximum Partical Size.	5μm

Environmental Conditions.
For operation within performance specification

Ambient temperature range;	15°C to 30°C
Ambient relative humidity;	10% to 80%

Safety.

The system is designed to be safe when the following conditions apply:
The system is located indoors in dry conditions.
Fluctuations in the mains supply voltage do not exceed ± 10%
The altitude does not exceed 2000m.
The ambient temperature is between 5°C and 40°C.
The ambient relative humidity does not exceed 80% for temperatures up to 31°C, decreasing linearly to 50% at 40°C.

All covers are in place and correctly fitted.

Additional Requirements.

All equipment and documentation supplied must comply with current relevant UK standards and CE regulations.