出國報告(出國類別:實習)

實習『超音波飼水流量量測系統』維護技術並執行 FAT 查證

服務機關:台灣電力公司(第一核能發電廠)

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赴派國家:美國

出國期間:97 年 1 月 13 日~97 年 1 月 26 日

報告日期: 97 年 2 月 4 日

行政院及所屬各機關出國報告提要

出國報告名稱：

實習『超音波飼水流量量測系統』維護技術並執行 FAT 查證

頁數 54 含附件：■是□否

出國計畫主辦機關/聯絡人/電話

台灣電力公司/陳德隆/02-2366

出國人員姓名/服務機關/單位/職稱/電話

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出國類別：□1 考察□2 進修□3 研究■4 實習□5 其他

出國期間：97.01.13~97.01.26 出國地區：美國

報告日期：97.01.30

分類號/目

關鍵詞：

內容摘要：(二百至三百字)

本廠小幅度功率提昇(2%以下功率提昇)，主要係藉由使用超音波流量計(UFM)改善飼水流量量測之不準度，使得到更精確熱功率之計算，以做為電廠功率提昇之依據。而美國 CAMERON 公司所製造的 LEFM Check 與 LEFM Check Plus 之 UFM 已獲得美國核管會(NRC)認可做為

核能電廠小幅度功率提昇之儀器。

此次出國主要為參訪美商 CAMERON 公司及 Alden 實驗室，於參訪美商 CAMERON 公司期間，除針對超音波飼水流量量測系統控制盤執行 FAT 查證外，另向原廠技術人員學習本系統之日常維護、控制盤面操作及故障診斷經驗。於參訪 Alden 實驗室期間，除了解其實驗室使用之測試設備及其使用測試之原理為何外，並確認實驗室現場管路之配置與電廠所提供之資料是否相符，詢問所測試之流量計於不同流量及不同漩流之情況其測試意義為何，且於參訪期間實際查證測試所獲得之流量計參數是否正常。

目　　次

壹、目的

本廠預定於#2機 EOC-22及#1機 EOC-23執行小幅度功率提升計劃，其中「超音波飼水流量量測系統採購安裝案」已於96年9月12日決標。依照採購合約內容，本廠應派員前往美國 CAMERON 公司(Pittsburgh, PA)針對 LEFM CheckPlus Electronic Units 執行 FAT 查證及至 Alden Research Laboratories(Boston, MA) 針對 LEFM CheckPlus Flow Elements 執行參數校驗查證。

超音波飼水流量量測系統，因精確度要求非常高，故所須之安裝、測試、校正、維護及操作等工作，需派員赴美國超音波流量計量測系統製造廠家及流量校正實驗室研習，以獲取原廠維護技術及經驗。因此本廠認爲有必要派員參加這次的系統模擬測試，以期將來電廠機組於運轉期間能更有效率的處理可能面臨的問題。

貳、行程

日　期	行　程　內　容
97.01.13~97.01.14	往程(Taipei － Pittsburgh, PA)
97.01.15~97.01.17	赴 CAMERON 公司研習超音波飼水流量量測系統儀控設備之定期測試、維護、操作及故障診斷，並執行 FAT 查證。 ★97.01.15-查證 FAT 程序書 TP203、TP203-1、TP203-2 、TP203-3 之執行結果 ★97.01.16-查證 FAT 程序書 TP203-4、TP203-5、TP203-6 之執行結果 ★97.01.17-查證 FAT 程序書 TP203-7、TP203-8 之執行結果並學習系統操作步驟
97.01.18	Pittsburgh, PA－Boston, MA
97.01.19~97.01.20	星期六、日，整理參訪資料
97.01.21~97.01.24	赴 Alden Research Laboratories 研習 Caldon 廠家超音波流量量測系統全尺寸安裝測試校正方法及校正數據查證。 ★97.01.21-UNIT 2 LOOP A 管路測試 ★97.01.22-UNIT 1 LOOP A 管路測試 ★97.01.23-UNIT 1 LOOP B 管路測試 ★97.01.24-UNIT 2 LOOP B 管路測試，管路測試預計到 97.01.28 結束
97.01.25~97.01.26	返程（Boston, MA － Taipei）

參、公差紀要

本廠所進行之小幅度功率提升計劃，其「超音波飼水流量量測系統採購安裝案」之軟體、硬體設備皆由美商 CAMERON 公司所提供，由富迪斯公司代理其在台銷售業務。本套設備於送達本廠前，除 CAMERON 公司須先對控制盤執行 FAT 程序書外，尚須經由 Alden 實驗室模擬電廠實際環境配置管路，以執行流量計不準度之參數計算。

出國期間首先參訪美商 CAMERON 公司，針對超音波飼水流量量測系統控制盤執行 FAT 查證，另向原廠技術人員學習本系統之日常維護、控制盤面操作及故障診斷經驗。其後參訪 Alden 實驗室，除了解其實驗室之設備及其使用測試之原理為何外，並確認實驗室現場管路之配置與電廠所提供之資料是否相符，詢問所測試之流量計於不同流量及不同漩流之情況其測試意義為何，且於參訪期間實際查證測試所獲得之流量計參數是否正常。

此次同行人員尚包括核能研究所核工組周光暉博士與張欽章博士、Sargent&Lundy 公司計劃經理王同陸博士以及富迪斯公司張晏銓工程師等人，以下簡述此次實習及查證之情形:

一、美商 CAMERON 公司參訪與說明

(一) 美商 CAMERON 公司簡介

美商 CAMERON 公司總部位於 Houston,TX，其事業版圖包含 Drilling&Production System Group、Valves&Measurement Group。此次參訪單位為 Valves&Measurement Group 轄下之 Caldon Nuclear 部門，該部門位於 Pittsburgh, PA，其所生產之超音波流量量測系統廣泛應用於核能、石油、水力、國防等相關領域，於參訪期間，由其部門主管 Mr. Erine Hauser 為參訪人員介紹 CAMERON 公司之運作情況，詳附件 1。

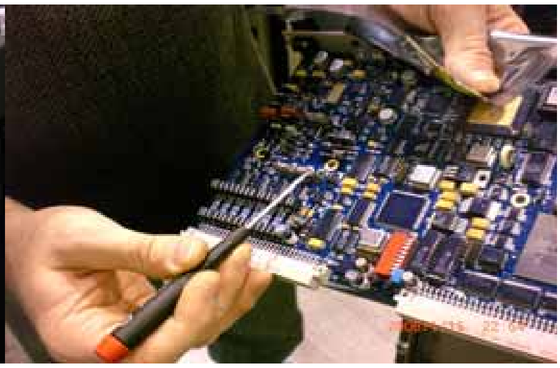
(二) 查證 CAMERON 公司控制盤 FAT 測試結果

CAMERON 公司之超音波飼水流量量測系統 FAT 測試程序書主要針對其控制盤之運作效能，依程序書之測試結果判定控制盤功能是否正常可用，以下針對其 FAT 測試程序書做一概略性之說明:

1. TP203 CONFIGURATION INFORMATION(儀控盤架構資料)—

1.1 記錄 Electrnoic Unit 序號及各項相關資料

1.2 記錄儀控盤內 VME Boards 序號及各項相關資料

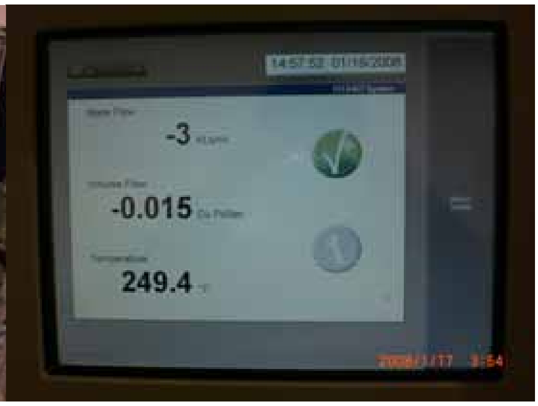


2. TP203.1 GENERAL EXAMINATIONS(一般性功能檢測)—

2.1 檢查 Electrnoic Unit 外觀、名牌及設備組件有無損害

2.2 於 VME Boards 未插入時，量測儀控盤內各項供給電壓

2.3 將 VME Boards 插入儀控盤並重新起動系統，檢查前盤指示燈號、電腦銀幕及觸控鍵之功能是否正常

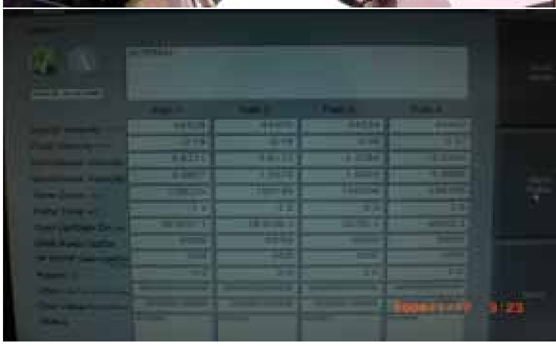


3. TP203.2 STEADY-STATE VOLTAGE AND NOISE TEST(儀控盤電源及雜訊檢測)—

3.1 於 APU 202B160 VL2 及 GSS Board 未插入控制盤時，變化儀控盤電源供給電壓，壓降(108Vac)及壓昇(132Vac)

3.2 量測及記錄+5Vdc、+12Vdc、-12Vdc、+24Vdc、+180Vdc 之直流電壓及交流雜訊電壓

3.3 觀察 APU 及 CPU 間之通訊有無異常



4.　TP203.3 ZERO BIAS FLOW TEST(零點偏移檢測)—

4.1 使用零流量測試套件及 300 英呎信號電纜線等測試設備

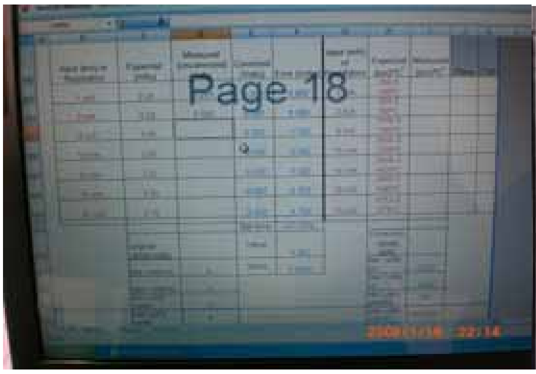
4.2 依序測試各音波迴路(Acoustic path)並記錄 T_{DOWN}、Delta T、Gain Up/Down

4.3 測試並記錄 APU Boards 阻抗高於 999 歐姆並觀查波形是否正常。

5.　TP203.4 ANALOG INPUT/OUTPUT TEST(類比輸出/輸入信號檢測)—

5.1 輸入類比信號(1~19 mA)觀察比對盤面輸出顯示值(0.25~4.75v)，記錄測試資料並計算零點及斜率，再將此兩數值輸入至控制盤中

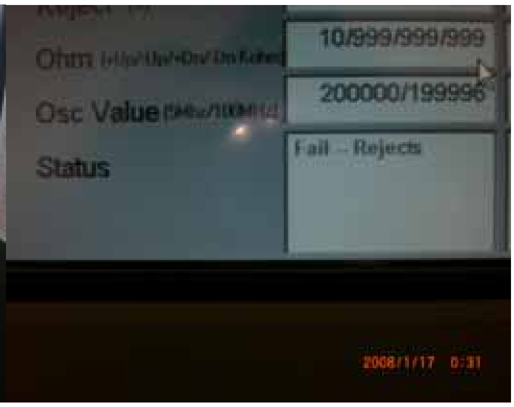
5.2 再輸入類比信號觀察比對盤面輸出顯示值是否相同[此測試分別測試流量計管路壓力(1~19 mA / 250~4750 psi)及水流溫度(1~19 mA / 30~570 ℃)]



6. TP203.5 CLOCK ACCURACY/TEST PATH VERIFICATION/IMPEDANCE TEST(系統時鐘及測試迴路檢測)—

6.1APU 模組 5MHz clock 信號測試(量測點 TP14&TP00) @4.9995~5.0005MHz

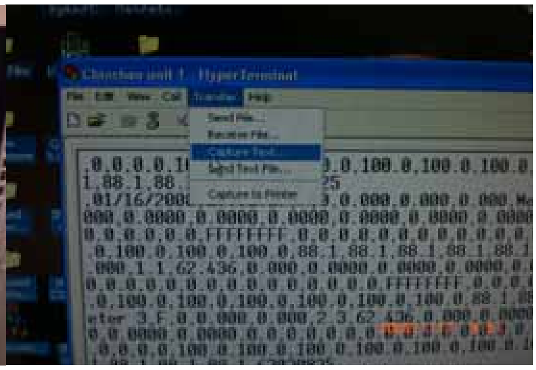
6.2 超音波轉換器測試迴路阻抗(10kΩ,+/-20%)。

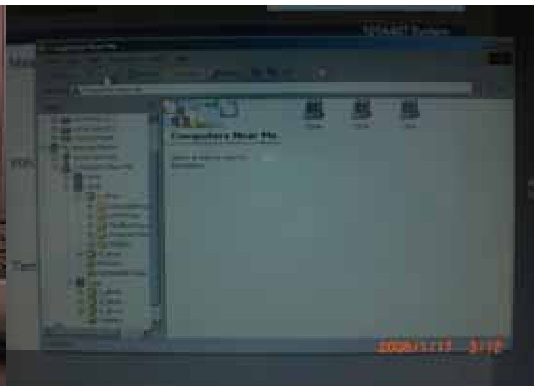


7. TP203.6 COMMUNICATION EQUIPMEN TEST(通訊設備檢測)—

7.1 檢測 CPU 以 COM2 port 使用 RS-232 直接與終端機通訊，確認終端機確實接收 CPU 傳輸之資料

7.2 檢測控制盤 Ethernet 網路之功能，使用 RJ-45 網路線連接 CPU A & CPU B，檢測 CPU A 模組上之"ENET"燈號正常，並查看 CPU A & CPU B 上網路芳鄰名稱是否顯示正常

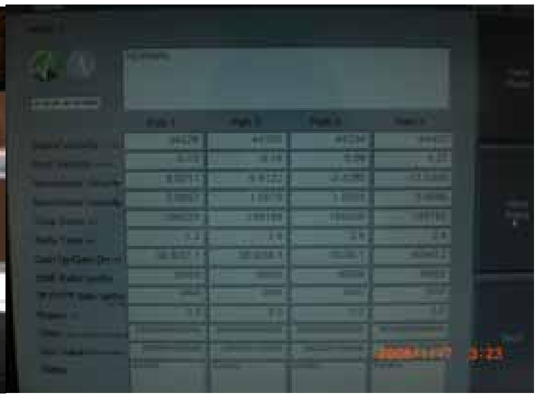
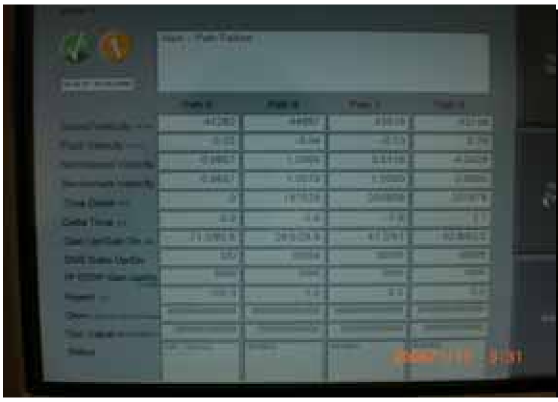




8. TP203.7 RELAY OUTPUT AND WATCHDOG TIME TEST(電驛輸出及系統計時器檢測)—

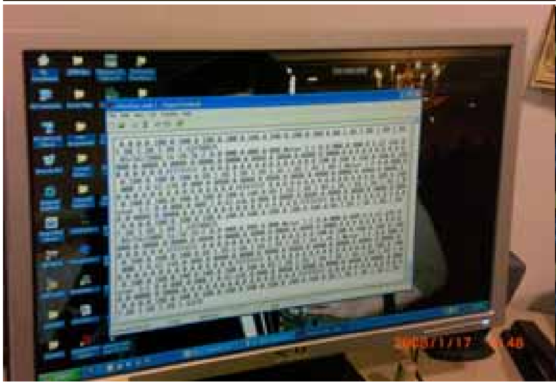
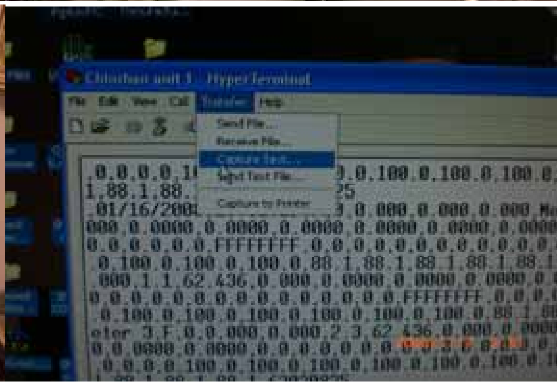
8.1 檢測 UFM 系統在 Maintenance 或 Failure 模式之電驛輸出

8.2 檢測系統計時器(測試系統電腦之 CPU 模組停擺時，可由計時器復歸 VME Bus，重新起動 CPU)

9. TP203.8 96 HOURS BURN-IN TEST(96 小時加電壓檢測)—

9.1 連續加電壓長時間 96 小時不中斷功能測試，無任何系統設備警訊及故障產生，APU 模組功能燈號正常, 3 個綠色 LED, 2 個紅色 LED 均正常、系統電腦 A 或 B 顯示, 及觸控功能均維持正常、由終端機接收 CPU 之訊號且記錄並觀察是否訊號維持正常。

上述九份 FAT 測試程序書皆針對控制盤之各項功能測試而編寫，觀看測試人員針對 FAT 測試程序書逐步測試，本人認爲對日後維護工作極有幫助，但因廠商已於參訪人員到達前先行測試完畢，雖有完整記錄測試結果，且經書面查驗並無不合格之處，但爲確保廠商測試結果之資料與實際情況無誤且欲學習其測試細節，本人強烈要求原測試人員針對 FAT 測試程序書所有之步驟，皆重新實作一次。期間，參訪人員於現場實地觀看，再逐一比對測試結果是否與原有測試資料相符，針對不懂的測試步驟

亦即時發問，經測試人員詳細的解說，參訪人員對控制盤操作與維護都有深刻印象。於經過詳細之查證後，可確認 FAT 測試資料相符。另一方面也藉此機會與原廠學習校驗實作之方式，以建立日後系統維護之技能。

二、Alden 實驗室參訪與說明

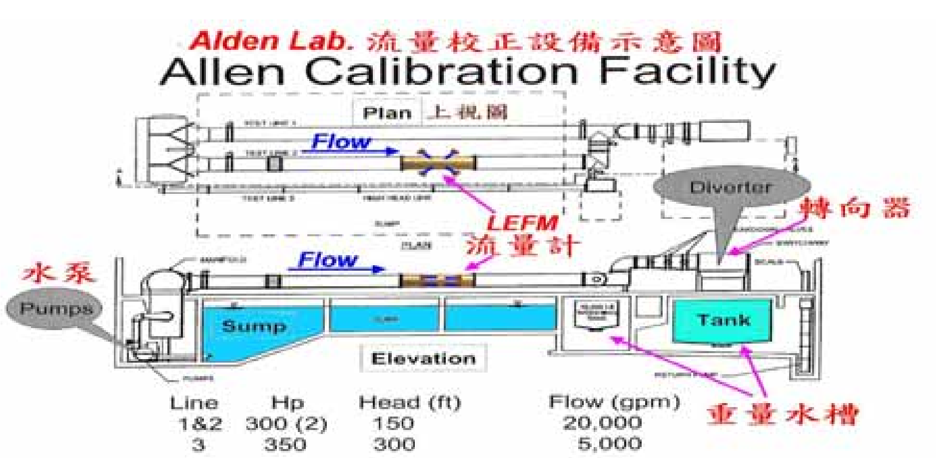
(一) Alden 實驗室簡介

Alden 實驗室原屬於伍斯特理工學院(Worcester Polytechnic Institute, WPI)，創立於 1894 年，後來獨立成為一私立之流體實驗室，是美國至今仍在運作之最古老的流體力學實驗室，從早期水力發電與航空技術的研究，持續至今不斷為工業界解決所

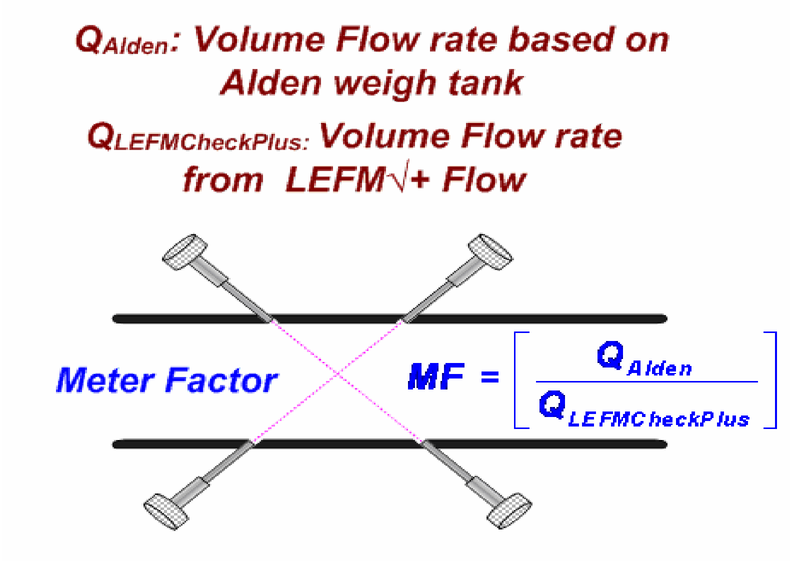
發生的問題，或爲工業界的產品做校驗，其下員工約有 70 名。Alden Lab. 目前共分爲下列五個部門：

- ✓ Air & Gas Modeling Group(空氣與氣體流動模擬組)
- ✓ Environmental Group(環境水文組)
- ✓ Hydraulic Modeling Group(流體力學模擬組)
- ✓ Numeric Modeling Group(數值分析模擬組)
- ✓ Flow Meter Calibration Group(流量計校驗組)

本廠此次所安裝之超音波飼水流量量測系統，乃由 CAMERON 公司委託 Alden 實驗室 Flow Meter Calibration Group(流量計校驗組)執行校驗測試，而 Flow Meter Calibration Group 乃爲美國國家標準科技研究所(National Institute of Standards and Technology,NIST)於美國境內在水流量計校驗上最大之獨立提供者。Flow Meter Calibration Group 之 Allen 水流量測試設備包括: 二台固定轉速之直立式送水泵，總共可提供之最大流量約爲 20,000 gpm、三個容量從 1000 磅到 100000 磅可秤重量的水槽、200000 加崙之集水坑、五條可分別適應尺寸從 1 英吋到 60 英吋流量計測試迴路及最長爲 72 英呎的水流量測試迴路，以重量分析法執行其流量校驗測試，其示意圖如下。



重量分析法之原理是將水從集水坑(Sump)用水泵打入流量計測試迴路再流進秤重水槽，由水槽內水之重量及所量測之時間，即可得到流速值，再將此流速值與超音波水流量計所量測之值比對，即可得知超音波水流量計之不準度(Uncertainty)，即超音波水流量計校正係數 (Meter Factor,MF)如下圖所示，詳附件二。



此重量分析方法符合國際標準組織準則 ISO 4185-1980 “Measurement of Liqui Flow in Closed Conducts-Weighing Method” 及美國機械工程師協會/美國國家標準科技研究所準則 ASME/NIST MFC-9M-1988 “Measurement of Liqui Flow in Closed Conducts by Weighing Method”，Alden Lab. 整體不準度如下圖所示。

Overall Flow Uncertainty

Mass 96276 lbm	Calibration	0.0363 %
	Buoyancy	0.0052 %
	Reproducibility	0.0160 %
	Loss	0.0021 %
	Resolution	0.0012 %
	Repeatability	0.0012 %
Time 139 seconds	Standard	0.0003 %
	Dead band	0.0003 %
	Resolution	0.0004 %
	Repeatability	0.0008 %
Density Temperature 91F	Standard	0.0026 %
	Impurities	0.0100 %
	Reproducibility	0.0104 %
	Resolution	0.0010 %
Diverter	Inclusive	0.0100 %
Combined Standard Uncertainty	Uc	**0.044 %**
Expanded Uncertainty	U	**0.088 %**

ALDEN

(二)Alden Lab. 流量計參數測試現場查證

1.超音波飼水流量量測系統(Loop A & Loop B)在 Alden Lab.流量校正測試之內容

1.1 測試不同之 Hydraulic Model 以確認 LEFM √+流量計不受不同之 Flow Profile 影響精確度

- 超音波 LEFM √ +流量計(Spool Piece)置為水平測試
- 超音波 LEFM √ +流量計(Spool Piece)轉為直立測試
- 於超音波 LEFM √ +流量計(Spool Piece)置為直立時，加入 Mitsubishi Flow Conditioner(MFC)整流測試
- 取走 Mitsubishi Flow Conditioner(MFC)加入半月型檔板，來造成旋流(Swirl)測試



1.2 測試 5 段不同之流量，以確認 LEFM √+流量計不準度

- 以約 17200 gpm 測試，每段取 5 次
- 以約 6800 gpm 測試，每段取 5 次
- 以約 13750 gpm 測試，每段取 5 次
- 以約 2500 gpm 測試，每段取 5 次
- 以約 10300 gpm 測試，每段取 5 次
- 當管路加入半月型檔板來造成旋流(Swirl)測試時，會因管路震動過大，而須適當調整測試之流速值。

1.3 Bypass Line 之 Hydraulic Modem 及測試之流量與上述略有不同，因此管平時應爲零流量狀態，故 Bypass Line 之重點在於閥之洩漏率，其 Hydraulic Model 如下所示

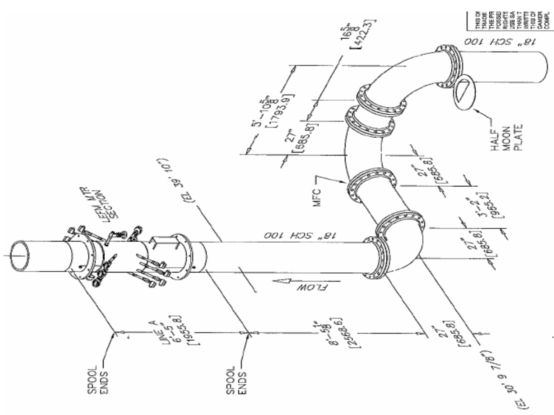
- 超音波 LEFM √ +流量計(Spool Piece)置爲水平測試
- 超音波 LEFM √ +流量計(Spool Piece)轉爲直立測試
- 於超音波 LEFM √ +流量計(Spool Piece)置爲直立時，加入 Mitsubishi Flow Conditioner(MFC)整流測試

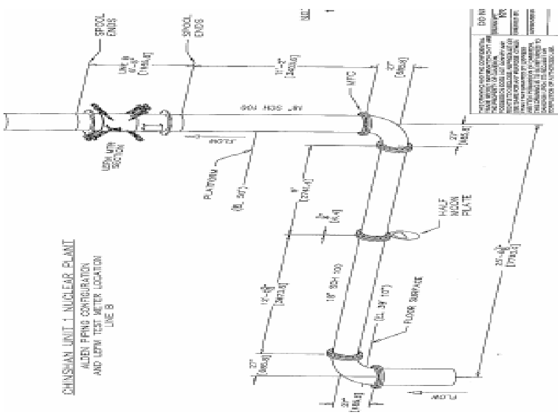
1.4 Bypass Line 之測試之流量如下所示

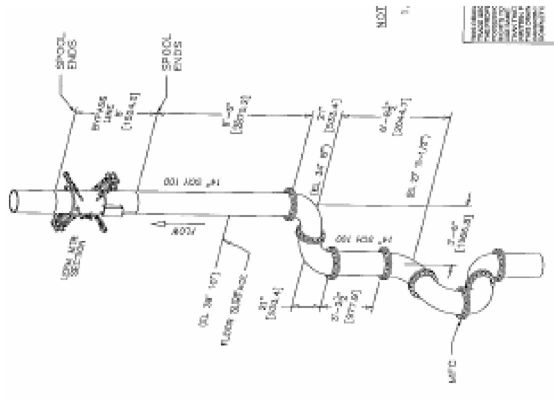
- 以約 16000 gpm 測試，每段取 5 次
- 以約 500 gpm 測試，每段取 5 次
- 以約 10000 gpm 測試，每段取 5 次
- 以約 100 gpm 測試，每段取 5 次
- 以約 2000 gpm 測試，每段取 5 次

2.超音波飼水流量量測系統(Loop A & Loop B)在 Alden Lab.流量校正測試之步驟

2.1 將管路依照圖面安裝。Alden Lab.現場管路之大小及長度依照圖面安裝完成，本廠因 Loop A/B 及 Bypass Line 路徑皆不相同，故查證配管方式正確與否亦為重點之一，圖面與 Lab.配管實況如下圖所示。





2.2 先將水道出口切換至排入集水坑(Sump)，啟動 Pump，開啟管路排氣孔，將管路之空氣排除

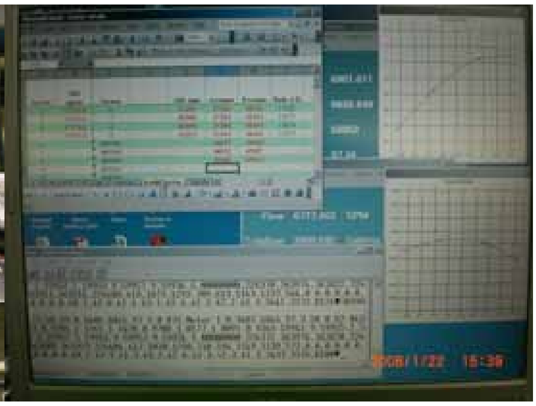

2.3 每個管路測試前皆須使用示波器量測 path1~8 之信號及雜訊大小並記錄於電腦中且觀察 path1~8 之 delta T 是否過大，若有 path 之上述數值異常則清潔 window 或檢查 Transducer 是否鎖緊若仍異常則更換 Transducer，待所有 Transducer 數值皆正常後，調整示波器記錄 path1~8 之 tau(音波送至收所須之時間)

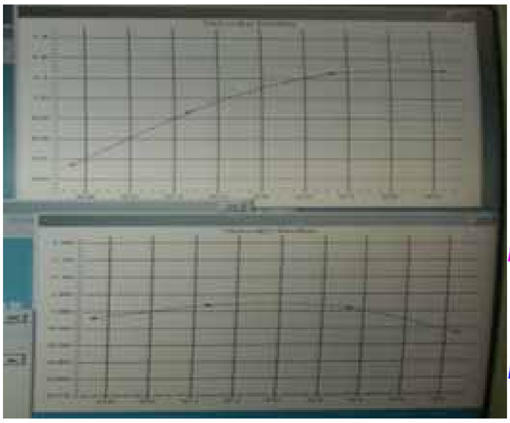

2.4 開始流量測試，調整控制閥之開度以控制流量，同時觀看 LEFM 盤面之 Volume Flow 數值達到所要測試之值

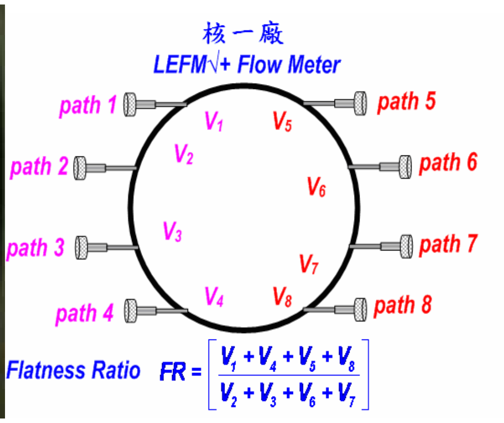

2.5 切換管路出水口至秤重水槽，Alden 人員開始計時，待秤重水槽滿水位時自動切回集水坑(Sump)

2.6 Alden 記錄計數時間、秤重水槽重量、volume flow、溫度，記錄完後，將秤重水槽內之水洩除

2.7 Cameron 將測試開始、結束時間及由 APU plane 1 & 2 所測得之脈波數及 ARL 測得之時間差及 volume flow 一併輸入至電腦中







2.8 重覆流量校正測試之內容

3.超音波飼水流量量測系統(Loop A & Loop B)在 Alden Lab.流量校正測試之結果(測試期間 97.01.21~97.01.24)，詳附件三。

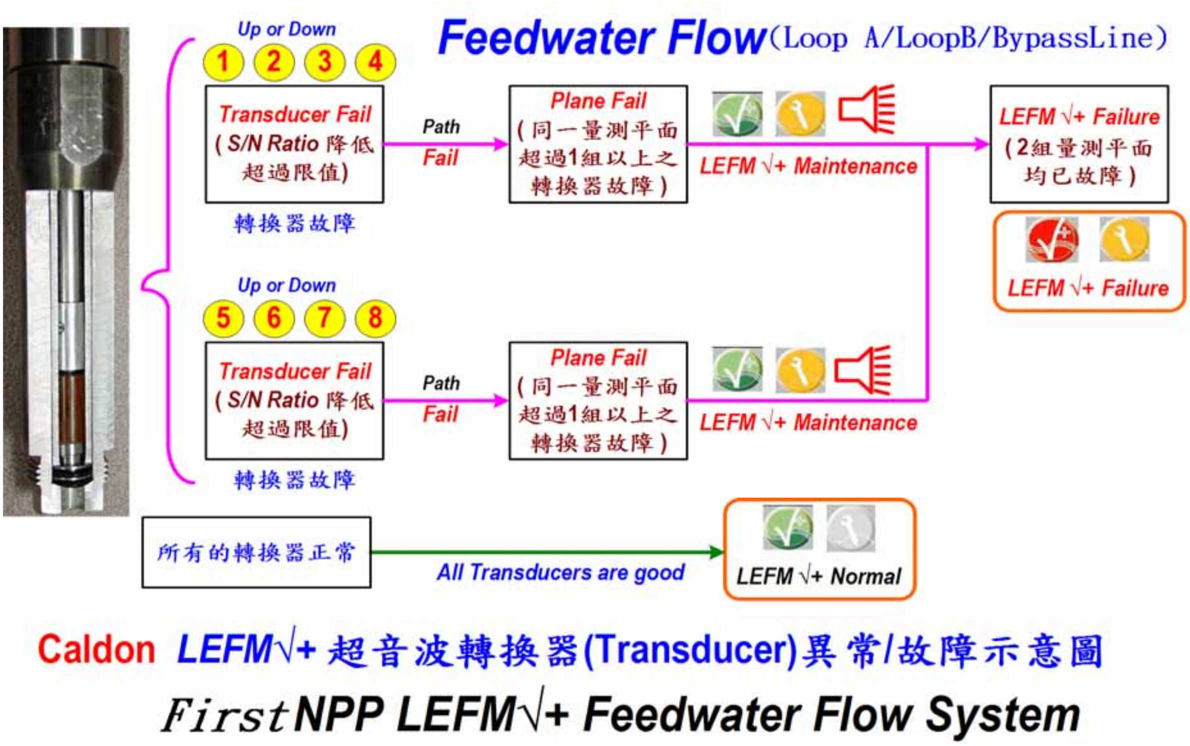
肆、心得與建議事項

一、於參訪CAMERON公司期間，感受該公司 FAT 測試技術人員實事求是之精神，完全依照程序書逐步執行不投機取巧，這點和本廠同仁極爲相似，對參訪人員提問之問題也都能給予滿意之答覆。而其部門主管 Mr. Erine Hause 陪同參與 FAT 查證及 Alden Lab. 參數測試，對參訪人員所要求之建議事項或待改進之處皆能盡力配合不推脫，令參訪人員對於本廠「超音波飼水流量量測系統採購安裝案」順利施工充滿信心。

二、Alden Lab.受工業界之委託，建立了許多實驗模型，這些模型均是依實物比例縮小而建造，且都是由 Alden Lab 的工作人員自行設計完成。而流體實驗室之測試包括水流及氣流，服務範圍涵蓋各行各業，包括核能電廠、燃煤或燃油火力電廠、流量儀器製造業、相關漁飼行業，及港灣研究相關單位等。從 Aldon Lab 所設計及建構的測試設施，以及工作人員對於測試品質的要求，可以看出其充分展現做爲一個專業實驗室所具有的技術與能力，以及爲何其能自主生存之道。

三、於 CAMERON 公司 FAT 測試時，得知任何一個飼水迴路(A-LOOP 或 B-LOOP 或 BYPASS LINE)上的一個量測平面(A-PLAN 或 B-PLAN)之 Transdurcer 故障時，此飼水量測系統即進入 Maintenance Mode。因 Bypass Line 之功能主要爲量測洩漏率，若因其 Transdurcer 故障而致使機組降載，似乎喪失安裝此系統之精神。故建議若 Bypass Line 之關斷閥於關閉時， 若其

Transdurcer 故障，可不列入 AOT，以維持機組正常運轉，待大修時再進行更換，系統警報示意圖如下。



四、此次 FAT 測試查證或 Alden Lab.參數校驗，皆取得對方同意讓參訪人員親自參與，協助測試，不僅使測試報告之可靠度提高，同時亦增加參訪人員日後維護之實作經驗。

五、本套設備預計 97.02.18 運抵本廠，開箱會驗完成後控制盤置於模中旁之儀控模擬室執行 Warm-up test，由於 FAT 只測試簡單之網路功能，屆時仍須請電算組派員至現場先行測試控制盤與廠內 PPCRS 之網路連線及資料送收之功能，以期工程順利進行。

六、於核二廠大修期間，核研所雖每日皆派人員支援 MUR/UFM 工程施工及測試，但因支援人員不固定，致使無法確實掌握工程進度及狀況。故擬建請核研所應派固定人員於本廠 MUR/ UFM 工程施工期間支援，以協助此工程順利執行。

伍、附件

一、美商 CAMERON 公司簡介

二、Alden lab. Flow Uncertainty ASME Paper

三、參訪期間 Alden Lab. 流量校正測試之結果

Cameron's
Valves & Measurement Group

Division Name Here
Presenters Name Here
Date Here

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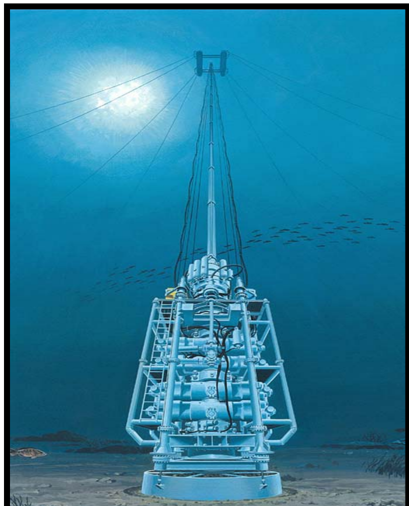
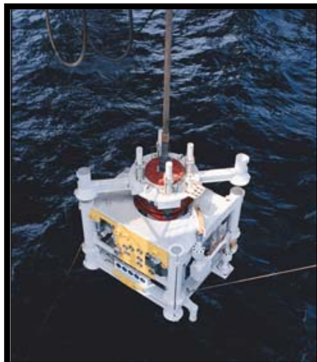




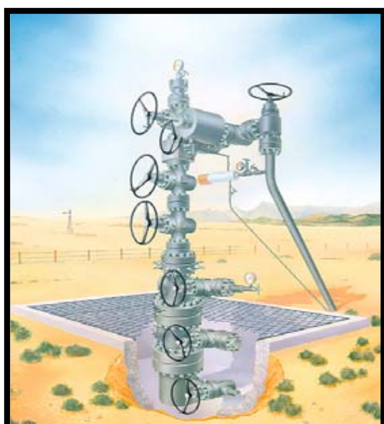

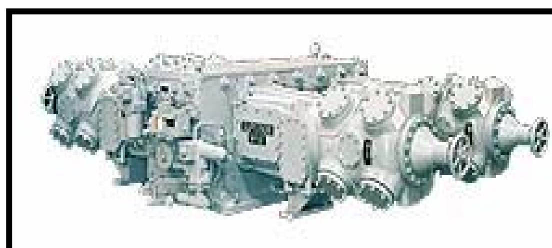
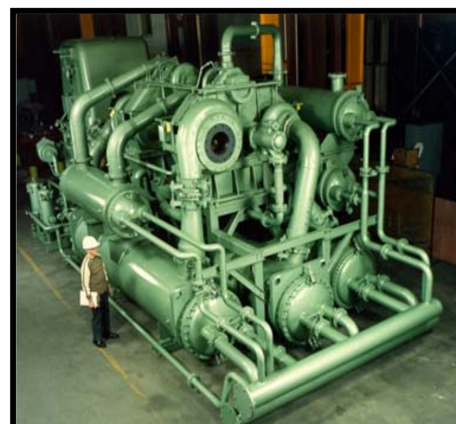

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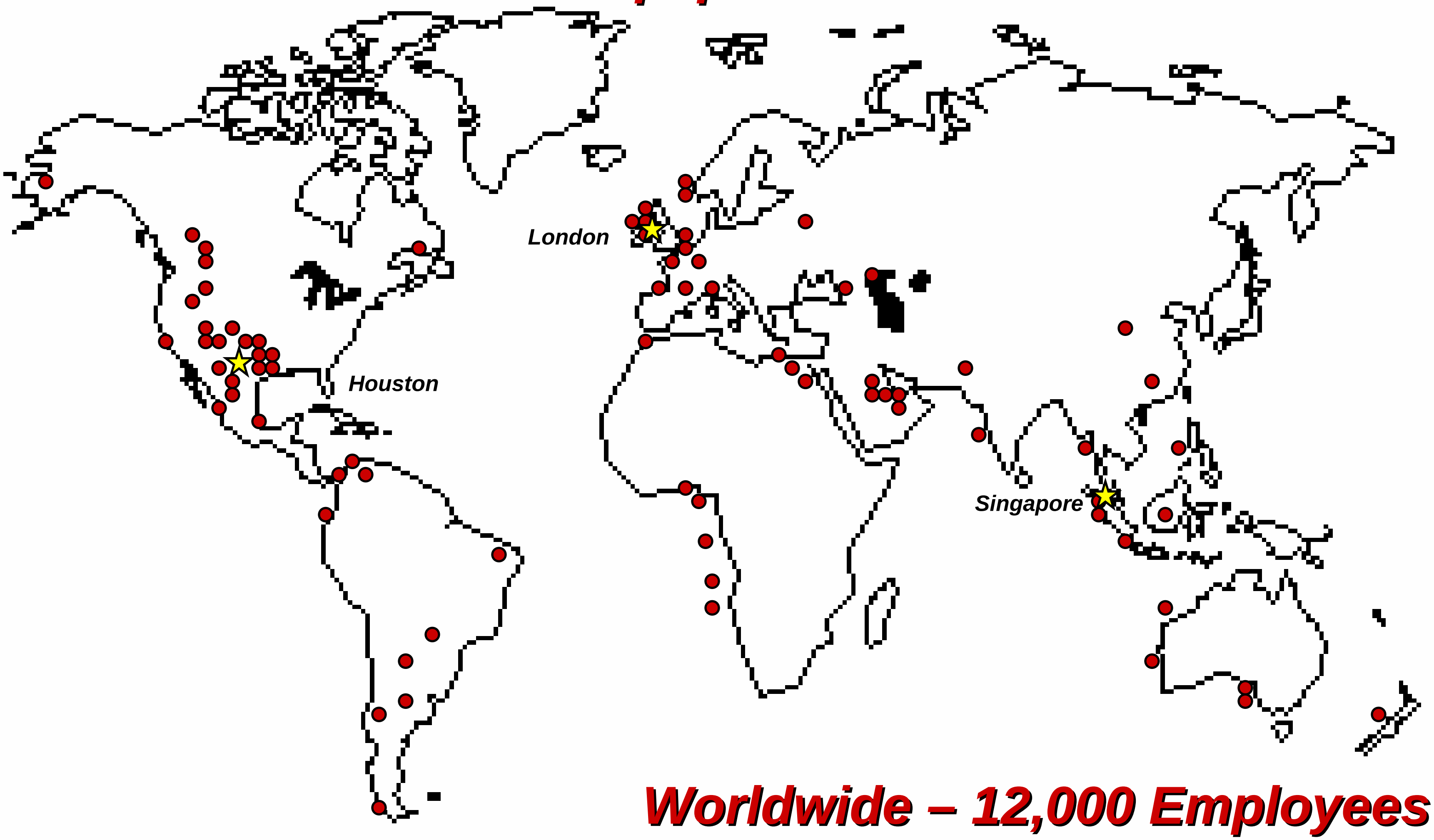

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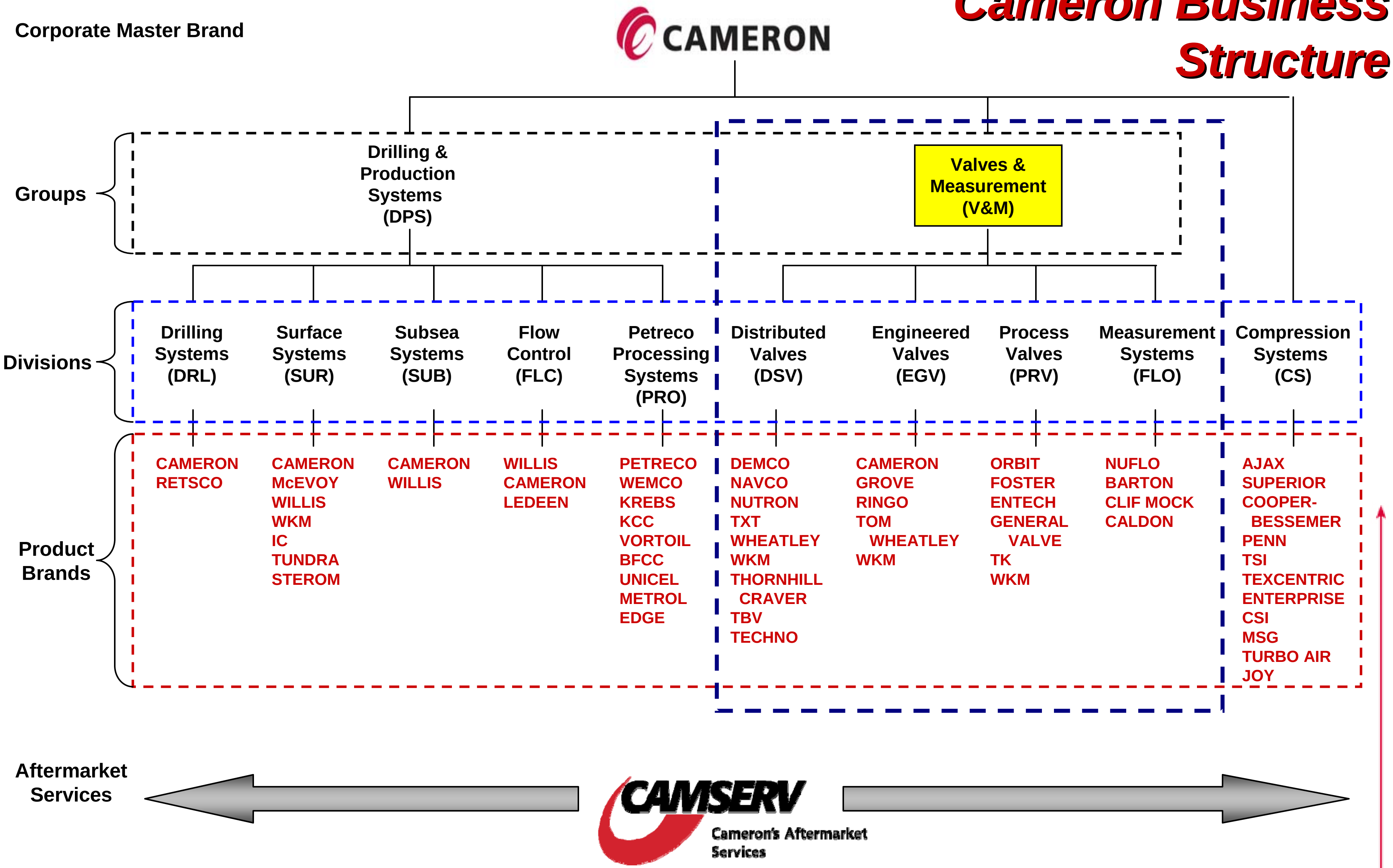

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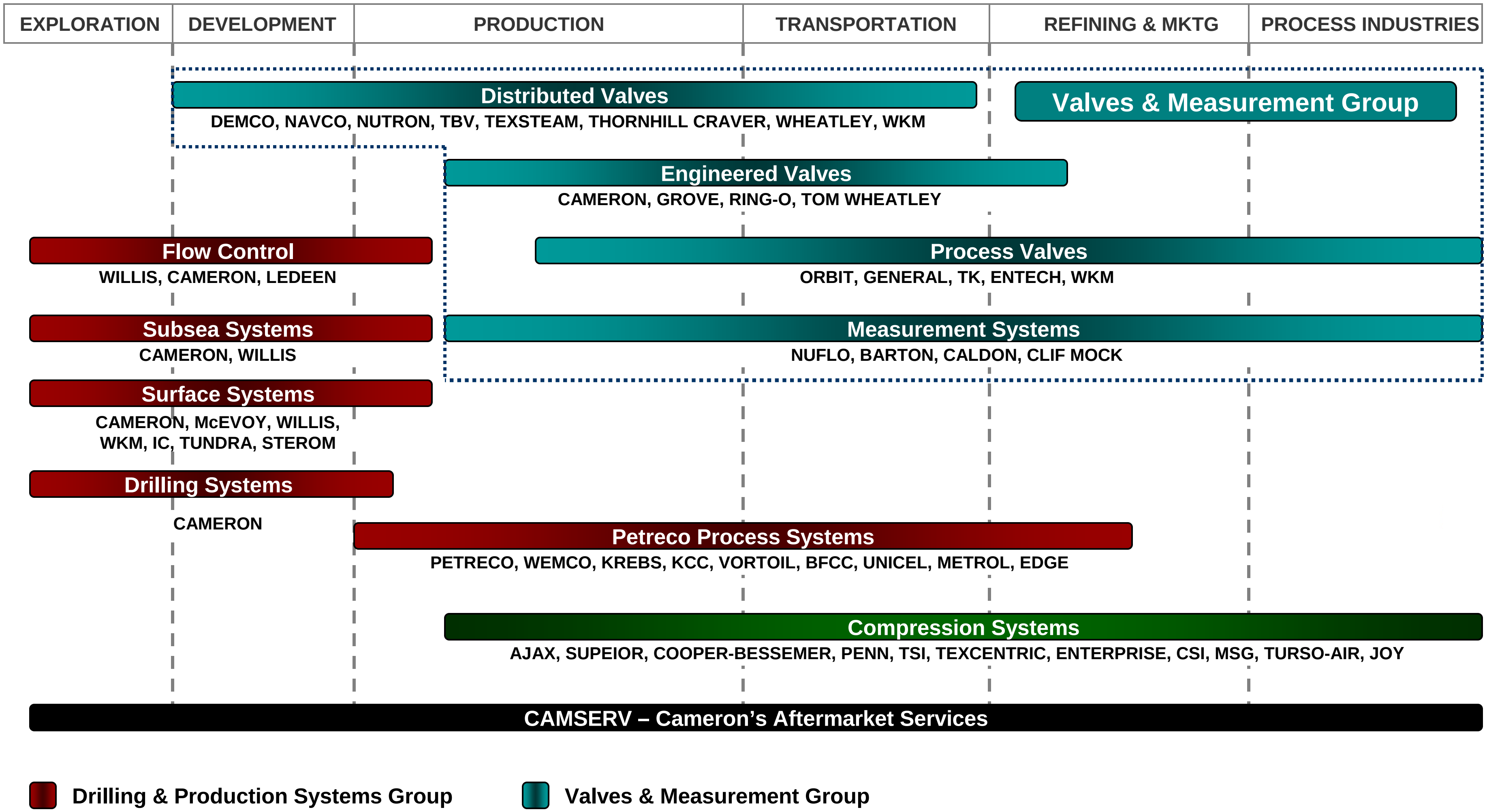

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Global Manufacturing & Support

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Texsteam/WKM/
Thornhill Craver

Edmonton, AB
Grove/ Nutron/
NAVCO/ Nuflo

Moore, OK
AOP

Ponca City, OK
Grove/ Ledeen

Houston, TX
Aftermarket
(Reconditioned)

Ville Platte, LA
Cameron/Grove/
Tom Wheatley

Jacarei, BRA
Grove

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Pittsburgh, PA
Caldon

Colico, Italy
Ring-O

Voghera, Italy
Grove/ Ledeen

Duncan, OK
NuFlo

Little Rock, AR
Orbit/Twin Seal/
WKM/ TruSeal

Hammond, LA
TK /Entech

Products Manufactured by Plant

City	Region	Country	Name	Division	Products / Comments
Colico	Europe	ITA	Ringo	EGV	Ringo Ball / Gate & Check
Edmonton	Alberta	CAN	Valgro	DSV	Grove - Ball / Gate Valves
Edmonton	Alberta	CAN	Nutron Manufacturing	DSV	Nutron Ball & Check Valves & Choke Valves / NAVCO Ball, Check and Gates
Hammond	Louisiana	USA	TK Valve	PRV	TK Ball Valves
Houston	Texas	USA	Aftermarket	PRV	Aftermarket Location (Reconditioned Valves)
Jacarei	Latin America	BRA	Cameron V&M - Brazil	EGV	Grove Ball Valves (assembly & test)
Little Rock	Arkansas	USA	CCV Little Rock	EGV	Orbit Ball Valves / General Twin Seal & TruSeal DB&B Valves / WKM Gate Valves
Millbury	Massachusetts	USA	TBV	PRV	TBV Ball, Gate & Globe Valves / Techno Check Valves
Oklahoma City	Oklahoma	USA	Demco		DEMCO Gate & Butterfly / WKM Ball & Hi-Perf. BFV / Wheatley Check Valves / Texsteam Super G Plug Valves / Thornhill Craver Chokes
Ponca City	Oklahoma	USA	Cameron Modern	EGV	Assembly & test of Grove Ball Valves 2-24" / Ledeen Actuation Assembly (Flow Control) & Valve Automation Center
Voghera	Europe	ITA	Grove	EGV	Grove - Ball, Gate and Check Valves
Voghera	Europe	ITA	Ledeen	FLC	Ledeen Actuators (Cameron's Flow Control Division)
Moore	Oklahoma	USA	AOP Industries	DSV	AOP Ball Valves
Viersen	Germany	GER	Entech	PRV	Entech Nozzle Checks
Ville Platte	Louisiana	USA	CCV Ville Platte	EGV	Cameron & Grove Ball Valves / Tom Wheatley Check Valves

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Proceedings of PWR2006
2006 ASME Power
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PWR2006-88058

CALIBRATION UNCERTAINTY OF PTC-6 FLOW SECTIONS

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ABSTRACT

PTC 6-2004 Performance Test Code on Steam Turbines [1] delineates fabrication and calibration requirements for throat tap flow nozzles with the purpose of obtaining the best feasible accuracy of flow measurement, a primary measurement to determine turbine performance. The Code requires nozzle discharge coefficient calibration results meet tight specifications for average value and rate of change with throat Reynolds number. Performance specifications were developed from large historical, empirical bases and an extensive theoretical analysis. Calibration uncertainty for PTC-6 Flow Meters using gravimetric flow measurement method in accordance with ASME/ANSI MFC 9M Measurement of Liquid Flow in Closed Conduits by Weighing Method [2] using a 100,000 lb capacity weigh tank is estimated. Calibration results are compared to Code requirements for about 330 meters with 1320 individual tap sets.

Keywords: Throat Tap Nozzle, Calibration, Flow Meter Uncertainty

BACKGROUND

ASME PTC 19.5-2004 Flow Measurement [3] defines flow calculations requiring a discharge coefficient to correct theoretical predictions.

$$q_m = 300.0\frac{\pi}{4}d^2C\varepsilon\sqrt{\frac{2\rho(\Delta P)g_c}{1-\beta^4}} \quad (1)$$

Were meters fabricated exactly geometrically similar, the discharge coefficient would be predicable with low uncertainty. As manufacturing tolerances and fabrication techniques vary, the predicted discharge coefficient value and uncertainty may be improved by calibration. PTC-6-2004 [1] requires calibration to verify meter performance to achieve best possible uncertainty. To determine the discharge coefficient uncertainty, mass flow, differential pressure, meter dimension, and fluid density uncertainties are estimated. Uncertainty elementary error sources are listed for a calibration system employing a 100,000 lb weigh tank and magnitudes estimated using methods in accordance with NIST Technical Note 1297 [4] Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.

FLOW MEASUREMENT

ASME/ANSI MFC-9M-1988 defines primary methods for gravimetric flow measurement systems. For the gravimetric flow measurement method, flow is diverted into a collection tank for a timed period, and the total collected mass is determined by static weighing. For each test point the flow through the test meter is constant with the magnitude controlled by settings pump speed and a downstream control valve. Flow is diverted into the weigh tank by a system designed to assure the test meter flow remains constant during diverter operation. For the 100,000 lb weigh tank facility, the diverter system includes a rectangular jet (a free discharge jet, 4" wide and 36" long) and hydraulically activated knife edge which diverts flow into the weigh tank. Mass flow is calculated by Equation 2.

$$q = \frac{w}{tB_c} \quad (2)$$

MASS MEASUREMENT UNCERTAINTY

The analysis of water mass measurement uncertainty follows methods defined in NISTIR 6919 Recommended Guide for Determining and Reporting Uncertainties for Balances and Scales [5]. Elementary error sources for mass measurement include: master standard uncertainty, transfer standard uncertainty, readability, repeatability, reproducibility, buoyancy correction, and effects of the process such as temperature, drafts, off center loading, electrical noise and vibration.

Alden's master mass standards are two 20 lb_m and one 10 lb_m masses, 50 lb_m mass total, certified by NIST on a ten year recurrence interval (which has demonstrated no variation in value). The master standards are used to calibrate an electronic balance having a resolution of 0.00022 lb (0.1 g). The balance is used to certify two hundred 50 lb_m transfer standard masses that are used to calibrate the weigh tank scale. The balance, master standards, and transfer standards are located in a specifically designed room to eliminate environmental effects such as drafts, temperature variations, and vibration. Test procedures address scale levelness, loading including shock and centering, master weight handling, and personnel training. Alden procedures require the balance to be calibrated prior to use in certifying the transfer standards (the balance calibration history indicates negligible reproducibility uncertainty). Balance sensitivity to load centering was evaluated and a template produces repeatable positioning of the master standards and the transfer standards. Table 1 shows the calibration uncertainty of the electronic balance including the primary mass standards NIST certified values and uncertainty. Multiple weighings of the master standards indicate the balance is repeatable to its resolution. The expanded uncertainty of the electronic balance is estimated at 0.00036 lb.

Influence Factor	Value lbs	Distri-bution	Standard Uncertainty lbs
Standards 50.000303 lb_m	0.0000096	Normal	0.0000096
Resolution	0.00022	Square	0.00013
Environmental Factors	0.00022	Square	0.00013
Combined Standard Uncertainty		u_c	0.00018
Expanded Uncertainty		U	0.00036

TABLE 1 ELECTRONIC BALANCE CALIBRATION

When purchased in 1968 the transfer standards were adjusted to the target reading of 50 lb_m. Table 2 lists the uncertainty of the calibration of a single 50 lb_m transfer standard. Reproducibility was determined from the standard deviation of multiple calibrations of a set of ten weights, a "tray". Transfer standards are used in a "lift" of 2,500 lb_m (fifty individual transfer standards or five trays) to calibrate the 100,000 lb_m scale. As all transfer standards are calibrated in the same manner, their uncertainties are not independent and the expanded uncertainty of a lift is estimated as 0.034 lb_m which is fifty times the expanded uncertainty of a single transfer standard. The transfer standards are certified on a two year recurrence and reproducibility due to wear or ageing between certifications is defined from multiple certifications.

Influence Factor	Value lbs	Distribution	Standard Uncertainty lbs
Balance Calibration	0.00036	Square	0.00021
Repeatability	0.00022	Square	0.00013
Readability	0.00022	Square	0.00013
Reproducibility	0.00016	Normal	0.00016
Environmental Factors	0.00022	Square	0.00013
Combined Standard Uncertainty		u_c	0.00034
Expanded Uncertainty		U	0.00068

TABLE 2 SINGLE TRANSFER STANDARD CALIBRATION UNCERTAINTY

Deviations of the measured values of individual transfer standards from the target value are independent and have a normal distribution. The historical average deviation and standard deviation of the two hundred transfer standard masses values from the target are 0.0002 lb_m and 0.0022 lb_m, respectively, with a normal distribution. The estimated combined standard uncertainty for combined lifts is estimated as a multiple of the single lift estimate. The sum of the measured masses of the two hundred 50 lb_m transfer standards is 9,999.94 lb_m with an expanded uncertainty of 0.136 lbs.

As the sum of the highest five measured deviations for all trays is less than 0.1 lb_m, (5% of the resolution of the scale) the individual calibrated values of lifts are not used in the calibration of the scales, but each lift is assigned a value of 2,500 lb_m for scale calibration. The maximum deviation from the target is added to the standards uncertainty. Calibration uncertainties for the first 10,000 lb_m increment applied to the scale are shown in Table 3 and includes values for repeatability and effects of the process such as temperature, drafts, off center loading, electrical noise and vibration.

Influence Factor	Estimated Value lb_m	Distribution	Estimated Standard Uncertainty lb_m
Standards	0.236	Normal	0.236
Readability	2.0	Square	1.155
Repeatability	0.58	Normal,	0.58
Process, etc.	3.5	Square	2.02
Combined Standard Uncertainty		u_c	2.41
Expanded Uncertainty		U	4.82

TABLE 3
INITIAL 10,000 lb CALIBRATION INCREMENT

The 100,000 lb_m scale is calibrated using substitution of loads method, since the scale capacity exceeds the calibration mass available (10,000 lb_m). In this method, after the maximum transfer standard mass is applied to the scale, water is substituted for the transfer standard mass to achieve the same scale reading, therefore, the same effective mass (including buoyancy effect). The 10,000 lb_m transfer standard masses are then loaded on the scale again to calibrate the next increment.

The buoyancy effect on the Transfer Standards is included using the ASME Test Standard MFC-9M-1988 [2] recommended methods. The scale calibration is input to the data reduction program as a lookup table to correct readings. Above 60,000 lb, the scale is calibrated in 2,500 lb increments, which makes linearity uncertainties negligible and uncertainties estimates are shown for 10,000 lb increments.

Reading lb_m	Standards lb_m	Resolution lb_m	Repeatability lb_m	Process lb_m	Substitution lb_m	Standard Uncertainty lb_m	Expanded Uncertainty lb_m
10,000	0.236	1.155	0.58	2.02	-	2.41	4.82
20,000	0.236	1.155	0.58	2.02	4	4.67	9.34
30,000	0.236	1.155	0.58	2.02	8	8.36	16.71
40,000	0.236	1.155	0.58	2.02	12	12.24	24.48
50,000	0.236	1.155	0.58	2.02	16	16.18	32.36
60,000	0.236	1.155	0.58	2.02	20	20.14	40.29
70,000	0.236	1.155	0.58	2.02	24	24.12	48.24
80,000	0.236	1.155	0.58	2.02	28	28.10	56.21
90,000	0.236	1.155	0.58	2.02	32	32.09	64.18
100,000	0.236	1.155	0.58	2.02	36	36.08	72.16

TABLE 4 INCREMENT METHOD SCALE CALIBRATION

TEST MASS MEASUREMENT

Table 5 lists uncertainty estimates for each elementary error source for each mass measurement. For convenience of combining additional terms, the uncertainties are converted to percent of reading for a typical 95,000 lb_m weigh tank filling.

Influence Factor	Estimated Value, %	Distribution	Standard Uncertainty %
Calibration	0.0363	Normal	0.0363
Buoyancy	0.0090	Square	0.0052
Resolution	0.002	Square	0.0012
Repeatability	0.002	Square	0.0012
Loss	0.0036	Square	0.0021
Reproducibility	0.016	Normal	0.016
Combined Standard Uncertainty	u_c		0.040
Expanded Uncertainty	U		0.080

TABLE 5 FULL TANK MEASUREMENT UNCERTAINTY

Buoyancy correction for water measurement is calculated with moist air density determined by perfect gas laws from atmospheric pressure, temperature, and relative humidity. Since the weigh tank is in an enclosed space below the floor, air temperature and humidity vary as the tank is filled and emptied. Air density is calculated with the average of the line and ambient temperatures at a relative humidity of 75%. The sensitivity of density calculations to these parameters has been evaluated and uncertainty estimates for the greatest expected deviations of temperature, pressure, and humidity have been included in calculation of buoyancy uncertainty.

Uncertainty due to reproducibility is estimated using control chart data from the calibrations recorded at six month intervals. The control chart in Figure 1 plots the deviation of the calibration correction in percent of reading from the average correction at that reading for each calibration point above 60,000 lb_m for seven calibrations. The minimum mass collected always exceeds 60,000 lb_m during testing and the current reproducibility standard uncertainty is estimated at 0.0123%.

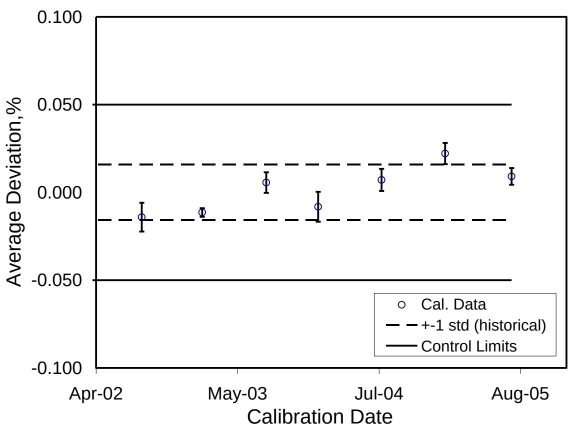

FIGURE 1 SCALE CALIBRATION CONTROL CHART

Splashing that occurs during knife edge operation may cause minor mass loss with an estimated uncertainty of 0.0021%. Repeatability uncertainty is estimated at 0.0004% using data recorded during scale calibrations. The total mass expanded uncertainty at 97,500 lb_m is 0.08%.

TIME UNCERTAINTY

Time of diversion is determined using a timer/counter (the primary instrument has a backup as a check) with a resolution of 0.001 sec. The counters are verified daily using a 1,000 hz signal from a 10 Mhz oscillator Time Standard.

A trigger controls the counter as the diverter knife edge passes the center of the discharge jet in both directions. Elementary error sources for time measurement include the Time Standard, counter resolution, repeatability, trigger deadband.

Alden's Time has a "time of day" display with a 1 second resolution. The display reading is certified weekly using the NIST WWV signal in order to have sufficient resolution,. Deviations from the NIST signal in a one week period (604,800 seconds) average 2 seconds or 0.0003%. The operation of the counter in the diverter timer is checked daily using the 1 Khz signal of the Time Standard. Timer repeatability is estimated at 0.002 second, or the sum of the resolution for the counter start and stop signals. Triggering has an uncertainty due to the deviation between the start and stop positions relative to the diverter jet (deadband). The switchway is hydraulically driven with a PID controller to obtain rapid, consistent knife edge travel. Trigger output and knife edge position as a function of time mapped using a linear potentiometer were recorded with a PC based data acquisition system for evaluation of trigger uncertainty.

Figure 2 plots knife edge position and trigger voltage output versus time in both directions. The jet boundary positions and centerline are also shown. The knife edge time of travel through the jet is about 0.25 seconds and the motion is essentially linear versus time within the jet boundaries.

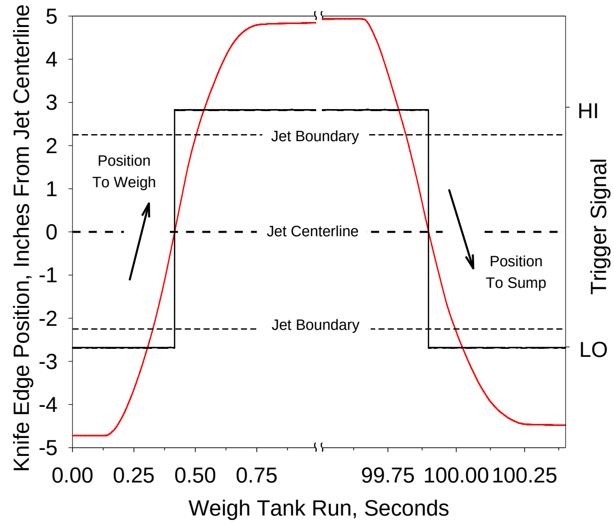

FIGURE 2 KNIFE EDGE MOTION

The timing uncertainty due to deadband, determined by the difference in position of the trigger signal in the two directions and the knife edge speed, is estimated at 0.0008 sec.

Influence Factor	Estimated Value, sec.	Distribution	Standard Uncertainty sec.
Time Standard	0.0003	Normal	0.0003
Resolution	0.0020	Square	0.0012
Trigger Deadband	0.0008	Square	0.0005
Repeatability	0.0020	Square	0.0012
Combined Standard Uncertainty	u_c		0.0018
Expanded Uncertainty	U		0.0036

TABLE 6 TIME MEASUREMENT UNCERTAINTY

The uncertainty due to the deviation of the trigger position from the jet center will be evaluated as a diverter uncertainty in the next section. Table 6 summarizes the time uncertainty estimates and calculates the total uncertainty.

DIVERTER UNCERTAINTY

ASME MFC-9M 1988 defines the optimum diverter design for minimum uncertainty. Requirements include a rapid knife edge operation relative to the total diversion time, and a linear variation of the flow diverted with distance with the triggering point it the midpoint of a uniform jet. Elementary error sources include trigger position, knife edge motion, and diverter jet velocity distribution. While the trigger position and knife edge motion are easily measured, see Figure 2, jet velocity distribution is not readily measurable. Deviation of the actual trigger location from the desired location at the jet centerline was measured with a 19,000 gpm flow to be about 0.010". Figure 2 indicates diverter motion is essentially linear and uniform in both directions. Assumption of highly skewed jet velocity distribution and including a variation of the knife edge speed while in the jet result in a diverter uncertainty estimate of 0.0075%. An alternative to evaluating each component of the diverter uncertainty is to evaluate uncertainty by the multiple switch method described in Appendix A of MFC-9M-1988. For a constant flow, multiple discharge coefficient measurements of a precise meter are recorded with the standard method (single diverter operation). Thereafter, multiple measurements are conducted with three and five diverter switches for a single weigh tank filling with the diversion time accumulated for each switch. Figure 3 plots the discharge coefficient for the single switch measurements and for multiple switches with a linear regression line versus the number of switches.

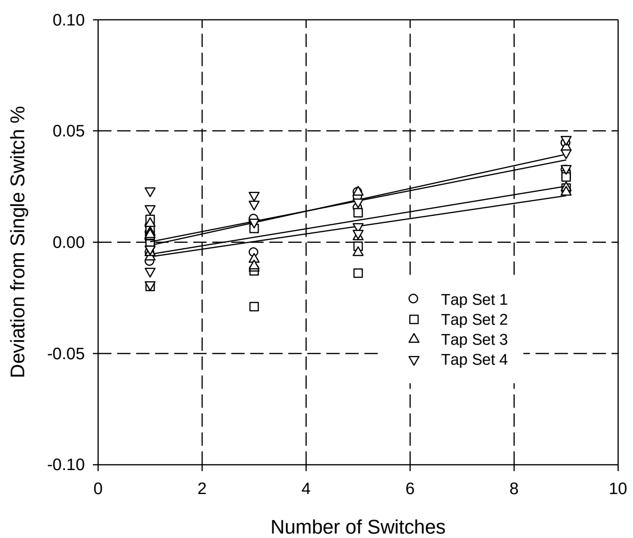

FIGURE 3 DIVERTER UNCERTAINTY

Theory dictates that the uncertainty should be cumulative with multiple switches (absolute uncertainty would increase linearly with number of switches). Test results for a 16" PTC 6 Nozzle at a Reynolds number of 4,170,000 (444"w.c. differential) indicated about a 0.04% change in discharge coefficient for nine switches or an uncertainty of +0.005% for a single switch. For conservatism an uncertainty of 0.01% is estimated.

DENSITY UNCERTAINTY

Density is calculated using PTB (1991) [6] equation from line temperature and uncertainty is calculated from the temperature uncertainty. Uncertainty of the equation formulation is estimated at 0.001%. An additional uncertainty occurs due to impurities. Thermometers are calibrated semi-annually using a maximum acceptable calibration deviation of 1°F. The master temperature standard used for thermometer calibration is NIST certified thermometer having an uncertainty of 0.25°F. Thermometer resolution is 0.1°F. Density uncertainty is calculated by partial differentiation of the equation describing density of water with temperature and calculating the density uncertainty from the temperature uncertainty.

Additional density uncertainty occurs due to contaminants in the water. Water quality analysis, conducted semi-annually, indicated the maximum suspended solids was less than 6 mg/l and dissolved impurities were about 100 mg/l, resulting in an uncertainty of 0.01%. Table 7 lists the elementary error sources for density determination and combines them to result in an expanded uncertainty of 0.035%.

I

Influence Factor	Estimated Value	Distri-bution	Standard Uncertainty,%
Formulation	0.001	Square	0.0006
Standard	0.0045 (0.25°F)	Square	0.0028
Resolution	0.0018 (0.1°F)	Square	0.0010
Reproducibility	0.018 (1°F)	Square	0.0115
Impurities	0.01	Normal	0.010
Combined Standard Uncertainty		u_c	0.0155
Expanded Uncertainty		U	0.031

TABLE 7 DENSITY UNCERTAINTY

Table 8 lists the uncertainty components of each elementary error source in the flow calculation (all of which have a sensitivity coefficient of 1. The total flow measurement uncertainty is estimated at 0.089% at the 95% confidence level. In addition to flow, elementary error sources for discharge coefficient include differential pressure, meter dimensions, thermal expansion, and local gravity.

Influence Factor	Standard Uncertainty %
Mass	0.040
Time	0.0036
Diverter	0.010
Density	0.0155
Combined Standard Uncertainty	0.045
Expanded Uncertainty	0.089

TABLE 8 OVERALL FLOW UNCERTAINTY

DIFFERENTIAL PRESSURE MEASUREMENT UNCERTAINTY

Differential pressure is measured with four sets of differential pressure transmitters with three ranges each, which are calibrated every two weeks with a dead weight tester having a manufacturer's uncertainty of 0.015%. The dead weight tester is periodically re-certified externally. Twice the manufacturer's value is estimated as the standard's uncertainty (verified by the re-certifications) to account for process uncertainty. The 16 bit data acquisition system is calibrated with the transmitters (an end to end calibration). Resolution of the system is 0.003%. Repeatability is estimated at 0.02% based on the calibration data using monotonically increasing pressure to maximum then decreasing. The value for reproducibility is based on control charts of the calibration data and includes the effects of zero drift. Uncertainty due to averaging the varying signal is estimated from the standard deviation of the measured signal and the number of points recorded. Local gravity is used in the calculation of pressure and the value used was determined by Worcester Polytechnic Institute's Physics Department in 1972 at 32.1625 ft/sec^2. A deviation of 0.0005 ft/sec^2, results in a standard uncertainty of 0.0015%

Influence Factor	Estimated Value %	Distribution	Standard Uncertainty
Standard	0.0173	Normal	0.0173
Resolution	0.0003	Square	0.00017
Repeatability	0.020	Normal	0.012
Reproducibility	0.0198	Normal	0.0198
Local Gravity	0.0015	Square	0.0009
Density Gradients	0.0075	Square	0.0043
Combined Standard Uncertainty	u_c		0.029
Expanded Uncertainty	U		0.058

TABLE 9 DIFFERENTIAL PRESSURE MEASUREMENT UNCERTAINTY

Differences between ambient and line temperatures between the meter and the pressure transmitters may cause a differential head measurement uncertainty, due to unequal temperature gradients in the high and low pressure lines. A 5° difference over a three foot height results in a pressure difference of 0.0006 ft, or 0.0075% of a minimum 8 foot differential pressure reading. The square root of differential pressure is used in the calculation of discharge coefficient, therefore, a sensitivity coefficient of 0.5 is applied to the differential pressure uncertainty estimate when it is combined with the remaining elementary error sources.

Meter dimensions, thermal expansion factor, and local gravitational constant are required by Equation (2). Initial measurement uncertainties of 0.0005" in both the throat and pipe diameter are assumed. Dimensions are affected by temperature, requiring calculation at operating temperature. The calculation includes the temperature at which the meter dimensions are measured, and an ambient temperature of 70°F is assumed for calculations when the measurement temperature is not given. Thermal expansion factor, α, given in MFC-3M-1989 [2], is about 5 10^{-6} 1/°F for stainless steel at ambient temperature. Assuming a 5°F uncertainty in the temperature difference (due to uncertainty of the temperature during the dimension measurements and calibration) results in an uncertainty estimate of about 0.0007%. A sensitivity factor of two is applied as diameter is squared

DISCHARGE COEFFICIENT UNCERTAINTY

Table 10 lists the combined the uncertainty estimates for each measurement component (with the sensitivity coefficient applied if different than 1). The example is for a typical high flow, time period, and high differential pressure which minimizes uncertainty due to transmitter reproducibility.

Parameter	Influence Factor	Standard Uncertainty	Weighting
Mass 96,276 lb_m	Calibration	0.0363	1
	Buoyancy	0.0052	1
	Reproducibility	0.0160	1
	Loss	0.0021	1
	Resolution	0.0021	1
	Repeatability		
Time 138.9 Sec.	Standard	0.0003	1
	Deadband	0.0048	1
	Resolution	0.0006	1
	Repeatability	0.0012	1
Density Temperature 91°F	Standard	0.0026	1
	Impurities	0.0100	1
	Reproducibility	0.0104	1
	Resolution	0.0010	1
Diverter	Inclusive	0.01000	1
Meter Dims. (12")	Thermal Expansion	0.00417	2
	Measurement	0.00007	2
	$(1-\beta^4)^{0.5}$	0.0010	1
Pressure 29 psid	Gravity	0.0008	0.5
	Calibration	0.0173	0.5
	Resolution	0.00017	0.5
	Repeatability	0.0120	0.5
	Reproducibility	0.0198	0.5
	Gradients	0.0043	0.5
	Averaging	0.0136	0.5
Standard Uncertainty		0.051	
Expanded Uncertainty		0.102	

TABLE 10 DISCHARGE COEFFICIENT UNCERTAINTY

Verifications

To check the uncertainty estimate of the discharge coefficient of PTC 6 nozzles, several calibration performance statistics were evaluated using historical calibration data from about 330 (1320 tap sets) nozzles. Repeatability is demonstrated by the cumulative frequency distribution of the precision index (Figure 4) as defined by required by PTC 6 para. 4-8.15.3 which indicates the median precision index is less than 0.015% percent or 50% of the Code requirement.

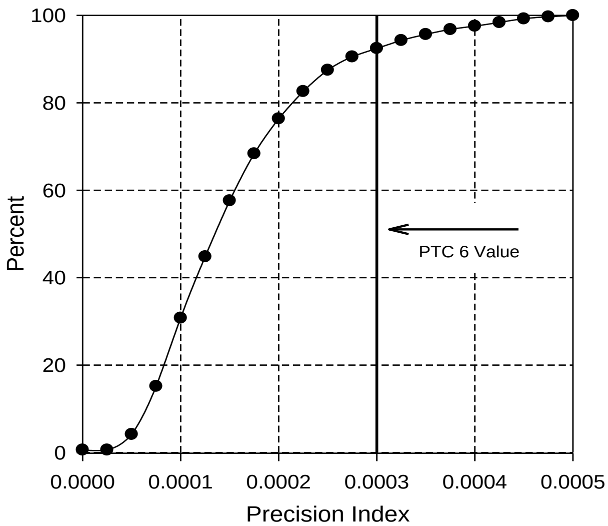

FIGURE 4 FREQUENCY DISTRIBUTION OF PRECISION INDEX

An offset of the average discharge coefficient from the predicted value with a high standard deviation would indicate either an unaccounted for error in the calibrations or manufacturing error. The frequency distribution of the difference of the average measured coefficient from the predicted coefficient (Figure 5) indicates approximately 85% of the tap sets met the Code requirement of less than ±0.25% deviation with the median deviation essentially at zero.

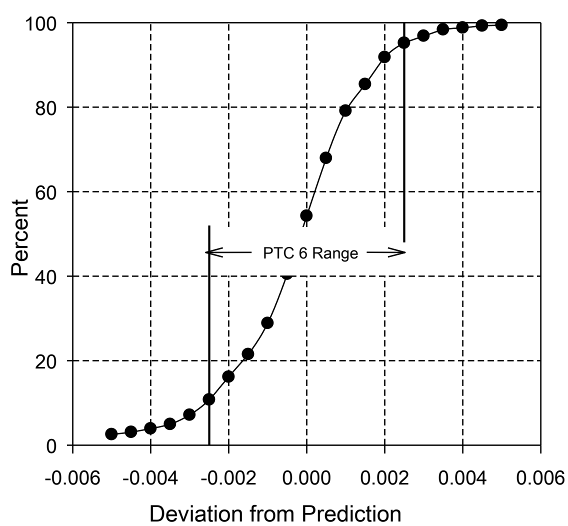

FIGURE 5 FREQUENCY DISTRIBUTION OF DEVIATION

The slope criterion has historically caused the most meter to failure calibration with about 55% of the tap sets passing the criterion and the median value of the test data being about +50% of the acceptable value of ±2.7e-10 value (Figure 6).

While detailed evaluation of other types of meters is beyond the scope of this discussion, experience indicates different meter types do not exhibit similar measured slopes greater than the their respective predictive equations If a consistent, undetected calibration error existed, the trend of greater measured slopes than predicted would be evidenced in all meters.

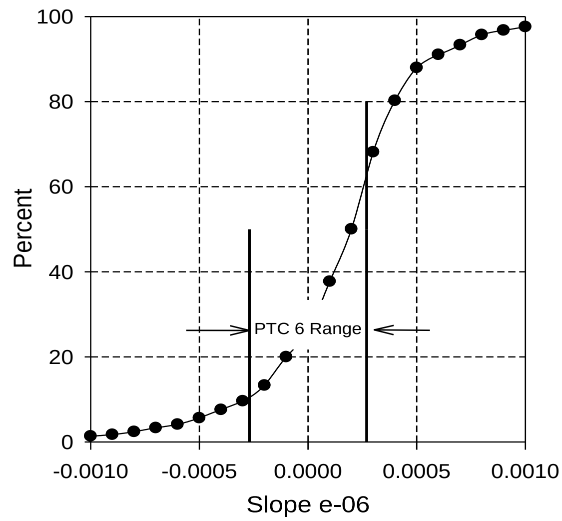

FIGURE 6 DISTRIBUTION SLOPE FREQUENCY

Inter-laboratory tests (proficiency testing) provide a confirmation of uncertainty estimates. Proficiency testing is complicated by the large range of laboratories flow capacities. A 16” PTC 6 nozzle was tested at NIST [7] and Alden in 1997 with mixed results. The large meter size and the high flow requirements resulted in high scatter at the NIST facility with higher uncertainty than expected. The uncertainty bands of the tests overlapped but individual test points deviated as much as 0.5%.

Typically, inter-laboratory tests have been conducted with meter sizes of 4" to 8" using turbine and orifice meters at relatively low Reynolds numbers to accommodate smaller capacity laboratories and low water temperatures. The most recent testing was conducted with NEL 200 mm Twin Orifice Plates 1999 [8] at seven laboratories. Testing was at relatively low Reynolds numbers, and optimum results were obtained with a 45,000 lb weigh tank with ambient water temperature. Alden’s results were within the uncertainty estimates of the several international laboratories. Internal comparisons between the two facilities indicate excellent internal consistency such that tests with the smaller weigh tank support the uncertainty of the largest facility. Two relatively recent comparisons with single laboratories have confirmed the uncertainty result in the 100,000 lb weigh tank. Ultrasonic flow meter testing, conducted by [9] at Alden and at National Metrology Institute - Japan in 10" and 16" sizes, indicated average deviations of 0.0% in the 16" tests and 0.03% and -0.04% for two 10" meters. Tests of two 12” averaging pitot tubes of differing design in natural gas and water [10] resulted essentially identical results including coefficient value and shape of the discharge coefficient results versus Reynolds number curve.

CONCLUSIONS

Calibrations are conducted over a range of flows and uncertainty is unique for each test point. Figure 7 shows estimated expanded uncertainty for a 16" PTC 6 flow nozzle indicating flow uncertainty is not a function of Reynolds number as full tanks are normally used and time uncertainty is small. Discharge coefficient uncertainty is a weak function of Reynolds number as differential pressure uncertainty increases with decreasing flow.

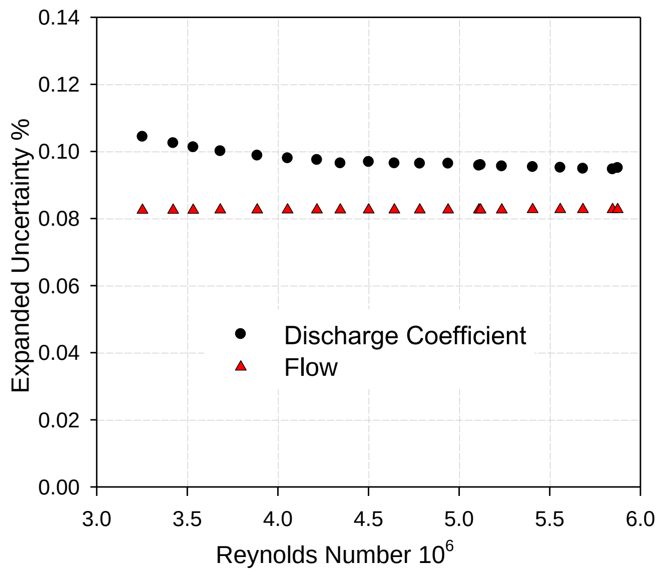

FIGURE 7 TYPICAL PTC 6 NOZZLE UNCERTAINTY

The methodology to estimate the uncertainty in measurement of flow and discharge coefficient determined as described above is applicable to a variety of differential producing flow meters.

NOMENCLATURE

q_m	=	mass flow, M/T
d	=	diameter
C	=	coefficient of discharge
ε	=	expansion factor of a flowing compressible fluid
ρ	=	density, M/L^3
P	=	Pressure, F/L^2
g_c	=	acceleration of standard gravity
β	=	diameter ratio, d/D
w	=	weight of water collected, lb_m
t	=	time, sec
B_c	=	buoyancy correction, dimensionless

REFERENCES

[1] Performance Test Code Committee 6 on Steam Turbines. "Steam Turbines Performance Test Codes: ASME PTC6-2004" 31 October 2005

[2] ASME Standards Committee MFC. "Measurement of Liquid Flow in Closed Conduits by Weighing Method" 28 February 1989

[3] Performance Test Code Committee 19.5 on Flow Measurement. "Flow Measurement Performance Test Codes: ASME PTC19.5-2004" 25 July 2005

[4] Taylor, Barry and Kuyatt, Chris. "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results." September 1994

[5] Miller, Val. "Recommended Guide for Determining and Reporting Uncertainties for Balances and Scales." NISTIR 6919, January 2002

[6] PTB: "Die Dichte des Wasser im internationalen Einheitensystem und der internationalen praltischen Temperaturskala vaon 1968," PTB Mitt., bol. 81, no 6, pp. 412-414, 1971

[7] Mattingly, Dr. George. "Report of Calibration of a Venturi Flowmeter: NIST Test No. 836/258366-97", 21 April, 1997

[8] Reader-Harris, Dr. M. J. "An Intercomparison Between NEL, NRLM, Delft Hydraulics, Alden Research Laboratories, CENAM and NIST Using a 200 mm Twin Orifice Plate Package in Water:", 24 September, 1999

[9] Augenstein, Don and Hannas, Ryan. "Profile Factor Calculation and Summary for the Alden/NMIJ Comparison Tests: Daldon ER-313 Rev. 1", December, 2002

[10] Personal correspondence

[11] Gowda, Vikram, Yeh, Tsyh-Tyan, Espina, Pedro I., and Yende, Nhlanhla P., "The New NIST Water Flow Calibration Facility"

[12] Bremser, Wolfram, et. al., "Traceability and Uncertainty of the German National Flow Rate Measurement Standard: Collection of Abstracts", 5th International Symposium, Fluid Flow Measurement, 7-10 April, 2002

ARL Test Designation	Caldon Test Number Rev 1	Spool Piece SN	Dates Tested
Cam21a	u2-a1	20106	2008/1/21
Cam21b	u2-a2		2008/1/21
Cam21c	u2-a3		2008/1/21
Cam21d	u2-a4		2008/1/21
Cam21e	u1-a1	20108	2008/1/22
Cam21f	u1-a2		2008/1/22
Cam21g	u1-b1	20109	2008/1/23
Cam21h	u1-b2		2008/1/23
Cam21i	u1-b3		2008/1/24
Cam21j	u1-b4		2008/1/24
Cam21k	u2-b1	20107	2008/1/24
Cam21l	#REF!		#REF!

CAM 21a - Test u2-a1

Date	**2008/1/21**
ID	**15.375**
Units	**63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**17178.3**	96.8	0.75	29.69	4,737,515	4.59E-04	17226.9	0.9972	17341.1	0.9906	17099.3	1.0046
2	**17167.7**	96.8	0.75	29.67	4,734,592	4.60E-04	17213.8	0.9973	17330.8	0.9906	17085.7	1.0048
3	**17138.6**	96.8	0.75	29.62	4,726,567	4.60E-04	17182.3	0.9975	17317.6	0.9897	17039.7	1.0058
4	**17184.4**	96.8	0.75	29.70	4,739,198	4.59E-04	17219.4	0.9980	17354.7	0.9902	17086.3	1.0057
5	**17166.8**	96.8	0.75	29.67	4,734,344	4.60E-04	17199.9	0.9981	17332.8	0.9904	17063.3	1.0061
6	**6861.8**	97.2	0.74	11.86	1,900,352	7.25E-04	6872.6	0.9984	6906.1	0.9936	6837.5	1.0035
7	**6858.4**	97.2	0.74	11.85	1,899,413	7.26E-04	6871.0	0.9982	6907.6	0.9929	6832.6	1.0038
8	**6851.6**	97.2	0.74	11.84	1,897,530	7.26E-04	6866.1	0.9979	6899.2	0.9931	6830.1	1.0032
9	**6855.7**	97.2	0.74	11.85	1,898,665	7.26E-04	6871.0	0.9978	6905.4	0.9928	6833.8	1.0032
10	**6859.2**	97.2	0.74	11.85	1,899,629	7.26E-04	6872.4	0.9981	6908.9	0.9928	6835.8	1.0034
11	**13733.80**	97.0	0.74	23.73	3,795,552	5.13E-04	13759.2	0.9982	13861.3	0.9908	13660.5	1.0054
12	**13728.80**	97.0	0.74	23.73	3,794,170	5.13E-04	13761.1	0.9977	13852.7	0.9911	13669.7	1.0043
13	**13728.90**	97.0	0.74	23.73	3,794,198	5.13E-04	13750.7	0.9984	13852.0	0.9911	13649.2	1.0058
14	**13733.90**	97.0	0.74	23.73	3,795,580	5.13E-04	13753.0	0.9986	13849.8	0.9916	13658.0	1.0056
15	**13730.60**	97.0	0.74	23.73	3,794,668	5.13E-04	13755.4	0.9982	13850.1	0.9914	13659.6	1.0052
16	**2522.33**	97.7	0.74	4.36	701,957	1.19E-03	2529.4	0.9972	2544.3	0.9914	2513.9	1.0033
17	**2521.88**	97.6	0.74	4.36	701,367	1.19E-03	2529.0	0.9972	2542.3	0.9920	2515.2	1.0027
18	**2522.22**	97.6	0.74	4.36	701,461	1.19E-03	2528.5	0.9975	2544.5	0.9913	2512.2	1.0040
19	**2521.65**	97.6	0.74	4.36	701,303	1.19E-03	2528.0	0.9975	2545.7	0.9906	2509.8	1.0047
20	**2522.45**	97.6	0.74	4.36	701,525	1.19E-03	2529.0	0.9974	2544.1	0.9915	2513.6	1.0035
21	**10262.10**	97.1	0.74	17.73	2,839,076	5.93E-04	10280.7	0.9982	10352.7	0.9912	10205.2	1.0056
22	**10261.20**	97.1	0.74	17.73	2,838,827	5.94E-04	10276.9	0.9985	10347.8	0.9916	10206.5	1.0054
23	**10265.30**	97.2	0.74	17.74	2,842,948	5.93E-04	10282.8	0.9983	10348.8	0.9919	10212.5	1.0052
24	**10262.60**	97.2	0.74	17.74	2,842,200	5.93E-04	10280.5	0.9983	10353.9	0.9912	10203.8	1.0058
25	**10267.20**	97.2	0.74	17.74	2,843,474	5.93E-04	10282.0	0.9986	10352.2	0.9918	10211.8	1.0054

CAM 21b - Test u2-a2

Date 2008/1/21

ID 15.375

Units 63094.578

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	17191.1	96.8	0.75	29.71	4,741,045	4.59E-04	17227.6	0.9979	17365.8	0.9899	17081.9	1.0064
2	17163.7	96.8	0.75	29.66	4,733,489	4.60E-04	17201.8	0.9978	17337.3	0.9900	17060.4	1.0061
3	17173.5	96.8	0.75	29.68	4,736,192	4.59E-04	17212.3	0.9977	17342.2	0.9903	17081.4	1.0054
4	17171.6	96.8	0.75	29.68	4,735,668	4.60E-04	17214.5	0.9975	17333.0	0.9907	17086.3	1.0050
5	17171.1	96.8	0.75	29.67	4,735,530	4.60E-04	17222.6	0.9970	17348.0	0.9898	17090.8	1.0047
6	6847.7	97.2	0.74	11.83	1,896,458	7.26E-04	6858.9	0.9984	6914.2	0.9904	6803.0	1.0066
7	6839.6	97.2	0.74	11.82	1,894,198	7.27E-04	6850.7	0.9984	6906.2	0.9903	6791.1	1.0071
8	6835.7	97.2	0.74	11.81	1,893,121	7.27E-04	6846.1	0.9985	6902.8	0.9903	6789.2	1.0068
9	6832.4	97.2	0.74	11.81	1,892,212	7.27E-04	6844.4	0.9982	6900.7	0.9901	6788.4	1.0065
10	6832.8	97.2	0.74	11.81	1,892,331	7.27E-04	6843.3	0.9985	6900.1	0.9902	6785.7	1.0069
11	13706.90	97.0	0.74	23.69	3,788,118	5.14E-04	13740.9	0.9975	13841.4	0.9903	13634.8	1.0053
12	13687.70	97.0	0.74	23.65	3,782,812	5.14E-04	13721.0	0.9976	13823.5	0.9902	13613.4	1.0055
13	13671.90	97.0	0.74	23.63	3,778,445	5.14E-04	13699.0	0.9980	13802.3	0.9906	13598.1	1.0054
14	13707.00	97.0	0.74	23.69	3,788,145	5.14E-04	13735.8	0.9979	13838.1	0.9905	13630.2	1.0056
15	13698.40	97.1	0.74	23.67	3,789,751	5.14E-04	13730.2	0.9977	13834.9	0.9901	13622.3	1.0056
16	2528.39	97.4	0.74	4.37	701,703	1.19E-03	2535.3	0.9973	2556.4	0.9891	2514.2	1.0056
17	2528.06	97.4	0.74	4.37	701,612	1.19E-03	2534.7	0.9974	2553.4	0.9901	2515.7	1.0049
18	2527.32	97.4	0.74	4.37	701,406	1.19E-03	2534.8	0.9970	2555.5	0.9890	2513.8	1.0054
19	2527.69	97.4	0.74	4.37	701,509	1.19E-03	2534.9	0.9972	2554.7	0.9894	2514.3	1.0053
20	2527.62	97.4	0.74	4.37	701,489	1.19E-03	2534.7	0.9972	2553.8	0.9898	2515.2	1.0049
21	10249.90	97.1	0.74	17.71	2,835,701	5.94E-04	10267.5	0.9983	10344.0	0.9909	10186.4	1.0062
22	10253.10	97.1	0.74	17.72	2,836,586	5.94E-04	10269.7	0.9984	10348.8	0.9908	10190.0	1.0062
23	10241.50	97.1	0.74	17.70	2,833,377	5.94E-04	10256.3	0.9986	10334.3	0.9910	10180.2	1.0060
24	10247.60	97.1	0.74	17.71	2,835,065	5.94E-04	10265.9	0.9982	10343.2	0.9908	10186.7	1.0060
25	10241.60	97.1	0.74	17.70	2,833,405	5.94E-04	10257.9	0.9984	10337.2	0.9908	10177.2	1.0063

CAM 21C - Test u2-a3

Date	**2008/1/21**
ID	**15.375**
Units	**63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**16533.0**	97.0	0.74	28.57	4,569,155	4.68E-04	16573.7	0.9975	16585.3	0.9968	16562.0	0.9982
2	**16522.4**	97.0	0.74	28.55	4,566,226	4.68E-04	16567.9	0.9973	16575.5	0.9968	16556.8	0.9979
3	**16532.1**	97.0	0.74	28.57	4,568,906	4.68E-04	16577.1	0.9973	16581.5	0.9970	16562.6	0.9982
4	**16531.4**	97.0	0.74	28.57	4,568,713	4.68E-04	16582.8	0.9969	16590.6	0.9964	16569.8	0.9977
5	**16539.1**	97.0	0.74	28.58	4,570,841	4.68E-04	16587.9	0.9971	16590.2	0.9969	16584.1	0.9973
6	**6869.8**	97.2	0.74	11.87	1,902,581	7.25E-04	6887.4	0.9974	6889.5	0.9971	6883.0	0.9981
7	**6864.2**	97.2	0.74	11.86	1,901,025	7.25E-04	6880.1	0.9977	6881.3	0.9975	6877.6	0.9981
8	**6859.2**	97.3	0.74	11.85	1,901,620	7.25E-04	6876.8	0.9974	6876.7	0.9974	6872.6	0.9980
9	**6860.5**	97.3	0.74	11.86	1,902,002	7.25E-04	6878.0	0.9975	6881.2	0.9970	6873.2	0.9982
10	**6861.5**	97.3	0.74	11.86	1,902,271	7.25E-04	6880.7	0.9972	6881.2	0.9971	6877.4	0.9977
11	**13692.20**	97.1	0.74	23.66	3,788,036	5.14E-04	13722.8	0.9978	13729.2	0.9973	13715.5	0.9983
12	**13678.60**	97.1	0.74	23.64	3,784,273	5.14E-04	13710.5	0.9977	13719.3	0.9970	13701.9	0.9983
13	**13682.60**	97.1	0.74	23.65	3,785,380	5.14E-04	13715.5	0.9976	13718.7	0.9974	13708.3	0.9981
14	**13690.40**	97.1	0.74	23.66	3,787,538	5.14E-04	13718.8	0.9979	13720.2	0.9978	13714.5	0.9982
15	**13667.10**	97.1	0.74	23.62	3,781,091	5.14E-04	13704.5	0.9973	13718.8	0.9962	13694.3	0.9980
16	**10321.80**	97.3	0.74	17.84	2,861,599	5.91E-04	10345.6	0.9977	10350.5	0.9972	10339.4	0.9983
17	**10313.60**	97.3	0.74	17.82	2,859,326	5.91E-04	10336.6	0.9978	10342.4	0.9972	10327.7	0.9986
18	**10311.50**	97.3	0.74	17.82	2,858,744	5.91E-04	10334.4	0.9978	10339.3	0.9973	10327.5	0.9985
19	**10318.80**	97.3	0.74	17.83	2,860,768	5.91E-04	10341.3	0.9978	10346.6	0.9973	10333.1	0.9986
20	**10312.20**	97.3	0.74	17.82	2,858,938	5.91E-04	10336.0	0.9977	10337.4	0.9976	10330.9	0.9982

CAM 21D - Test u2-a4

Date	**2008/1/21**
ID	**15.375**
Units	**63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMChec k Paths 5-8	MF Plane B
1	**11116.3**	97.4	0.74	19.21	3,085,103	5.69E-04	11163.8	0.9957	11191.2	0.9933	11136.1	0.9982
2	**11107.5**	97.5	0.74	19.20	3,084,403	5.69E-04	11156.2	0.9956	11181.8	0.9934	11122.1	0.9987
3	**11108.4**	97.4	0.74	19.20	3,083,835	5.69E-04	11156.6	0.9957	11188.5	0.9928	11120.8	0.9989
4	**11110.9**	97.4	0.74	19.20	3,083,835	5.69E-04	11159.3	0.9957	11192.4	0.9927	11126.0	0.9986
5	**11107.6**	97.4	0.74	19.20	3,082,688	5.70E-04	11154.5	0.9958	11184.7	0.9931	11125.2	0.9984
6	**5012.2**	97.3	0.74	8.66	1,389,585	8.48E-04	5030.0	0.9965	5038.0	0.9949	5020.3	0.9984
7	**5003.6**	97.3	0.74	8.65	1,387,190	8.49E-04	5021.0	0.9965	5034.6	0.9938	5006.5	0.9994
8	**5002.4**	97.3	0.74	8.65	1,386,849	8.49E-04	5021.2	0.9963	5029.6	0.9946	5011.4	0.9982
9	**5001.2**	97.4	0.74	8.64	1,387,970	8.49E-04	5020.1	0.9962	5033.4	0.9936	5005.1	0.9992
10	**5000.0**	97.4	0.74	8.64	1,387,637	8.49E-04	5018.4	0.9963	5031.7	0.9937	5004.7	0.9990
11	**7966.90**	97.3	0.74	13.77	2,208,731	6.73E-04	7995.1	0.9965	8009.4	0.9947	7980.0	0.9984
12	**7681.60**	97.3	0.74	13.28	2,129,634	6.85E-04	8003.1	0.9598	8018.0	0.9580	7991.5	0.9612
13	**7973.38**	97.3	0.74	13.78	2,210,527	6.73E-04	7995.2	0.9973	8012.1	0.9952	7979.2	0.9993
14	**7971.06**	97.3	0.74	13.78	2,209,884	6.73E-04	7994.4	0.9971	8021.6	0.9937	7967.1	1.0005
15	**7977.90**	97.3	0.74	13.79	2,211,780	6.72E-04	8004.2	0.9967	8018.0	0.9950	7988.6	0.9987

CAM 21e - Test u1-a1

Date 2008/1/22
ID 15.375
Units 63094.578

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**17167.2**	96.9	0.75	29.67	4,739,439	4.59E-04	17169.0	0.9999	17294.2	0.9927	17042.5	1.0073
2	**17153.0**	96.9	0.75	29.64	4,735,518	4.60E-04	17154.4	0.9999	17294.6	0.9918	17007.2	1.0086
3	**17144.7**	96.9	0.75	29.63	4,733,227	4.60E-04	17155.2	0.9994	17311.6	0.9904	17001.9	1.0084
4	**17150.7**	96.9	0.75	29.64	4,734,883	4.60E-04	17148.1	1.0002	17295.1	0.9917	16998.2	1.0090
5	**17141.5**	96.9	0.75	29.62	4,732,344	4.60E-04	17128.0	1.0008	17281.2	0.9919	16977.1	1.0097
6	**6858.3**	97.3	0.74	11.85	1,901,384	7.25E-04	6856.6	1.0002	6901.1	0.9938	6809.9	1.0071
7	**6857.4**	97.3	0.74	11.85	1,901,135	7.25E-04	6852.5	1.0007	6899.3	0.9939	6805.7	1.0076
8	**6849.9**	97.3	0.74	11.84	1,899,041	7.26E-04	6847.4	1.0004	6891.7	0.9939	6801.9	1.0070
9	**6849.8**	97.3	0.74	11.84	1,899,039	7.26E-04	6850.9	0.9999	6902.5	0.9924	6798.6	1.0075
10	**6847.4**	97.3	0.74	11.83	1,898,348	7.26E-04	6845.9	1.0002	6894.2	0.9932	6796.1	1.0075
11	**13819.80**	97.0	0.74	23.88	3,819,319	5.12E-04	13800.9	1.0014	13926.2	0.9924	13690.5	1.0094
12	**13829.00**	97.1	0.74	23.90	3,825,882	5.11E-04	13831.1	0.9998	13945.0	0.9917	13714.4	1.0084
13	**13811.20**	97.1	0.74	23.87	3,820,958	5.12E-04	13814.5	0.9998	13939.3	0.9908	13687.8	1.0090
14	**13830.70**	97.1	0.74	23.90	3,826,352	5.11E-04	13827.3	1.0002	13934.8	0.9925	13719.2	1.0081
15	**13813.10**	97.1	0.74	23.87	3,821,483	5.12E-04	13811.2	1.0001	13927.4	0.9918	13696.3	1.0085
16	**2482.67**	97.4	0.74	4.29	689,014	1.20E-03	2482.6	1.0000	2498.3	0.9938	2466.3	1.0066
17	**2482.21**	97.4	0.74	4.29	688,887	1.20E-03	2481.5	1.0003	2496.8	0.9942	2465.9	1.0066
18	**2482.07**	97.4	0.74	4.29	688,848	1.20E-03	2480.1	1.0008	2495.1	0.9948	2464.8	1.0070
19	**2480.69**	97.4	0.74	4.29	688,465	1.21E-03	2479.5	1.0005	2494.5	0.9945	2463.9	1.0068
20	**2480.24**	97.4	0.74	4.29	688,340	1.21E-03	2478.9	1.0005	2490.7	0.9958	2466.4	1.0056
21	**10214.50**	97.2	0.74	17.65	2,828,879	5.95E-04	10212.1	1.0002	10297.1	0.9920	10123.6	1.0090
22	**10206.40**	97.2	0.74	17.64	2,826,635	5.95E-04	10205.3	1.0001	10285.6	0.9923	10121.1	1.0084
23	**10212.00**	97.2	0.74	17.65	2,828,186	5.95E-04	10208.0	1.0004	10293.4	0.9921	10120.7	1.0090
24	**10207.90**	97.2	0.74	17.64	2,827,051	5.95E-04	10204.4	1.0003	10285.3	0.9925	10123.5	1.0083
25	**10206.10**	97.2	0.74	17.64	2,826,552	5.95E-04	10204.4	1.0002	10284.4	0.9924	10122.1	1.0083

CAM 21f - Test u1-a2

Date	**2008/1/22**
ID	**15.375**
Units	**63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**17172.3**	96.9	0.75	29.68	4,740,847	4.59E-04	17170.2	1.0001	17319.8	0.9915	17014.5	1.0093
2	**17160.9**	96.9	0.75	29.66	4,737,699	4.59E-04	17159.1	1.0001	17302.6	0.9918	17016.8	1.0085
3	**17152.2**	96.9	0.75	29.64	4,735,298	4.60E-04	17145.4	1.0004	17288.1	0.9921	17002.9	1.0088
4	**17170.1**	96.9	0.75	29.67	4,740,239	4.59E-04	17162.0	1.0005	17312.9	0.9918	17012.1	1.0093
5	**17157.3**	96.9	0.75	29.65	4,736,706	4.59E-04	17139.4	1.0010	17286.5	0.9925	16989.2	1.0099
6	**6850.2**	97.3	0.74	11.84	1,899,144	7.26E-04	6848.3	1.0003	6913.4	0.9909	6780.8	1.0102
7	**6846.2**	97.3	0.74	11.83	1,898,035	7.26E-04	6842.5	1.0005	6910.1	0.9908	6773.0	1.0108
8	**6843.9**	97.3	0.74	11.83	1,897,389	7.26E-04	6837.3	1.0010	6901.9	0.9916	6772.7	1.0105
9	**6847.0**	97.3	0.74	11.83	1,898,449	7.26E-04	6841.7	1.0008	6905.7	0.9915	6777.4	1.0103
10	**6844.7**	97.4	0.74	11.83	1,899,599	7.26E-04	6838.7	1.0009	6899.8	0.9920	6775.9	1.0101
11	**13768.09**	97.1	0.74	23.79	3,809,031	5.12E-04	13768.1	1.0000	13890.5	0.9912	13642.8	1.0092
12	**13767.47**	97.1	0.74	23.79	3,808,859	5.12E-04	13746.3	1.0015	13870.2	0.9926	13628.6	1.0102
13	**13771.22**	97.2	0.74	23.80	3,813,903	5.12E-04	13768.7	1.0002	13885.6	0.9918	13649.9	1.0089
14	**13771.41**	97.2	0.74	23.80	3,813,955	5.12E-04	13770.9	1.0000	13889.8	0.9915	13650.0	1.0089
15	**13761.39**	97.2	0.74	23.78	3,811,180	5.12E-04	13768.3	0.9995	13889.4	0.9908	13643.6	1.0086
16	**2483.81**	97.5	0.74	4.29	690,055	1.20E-03	2480.8	1.0012	2502.6	0.9925	2458.7	1.0102
17	**2483.34**	97.5	0.74	4.29	689,924	1.20E-03	2479.7	1.0015	2501.9	0.9926	2457.5	1.0105
18	**2482.37**	97.5	0.74	4.29	689,655	1.20E-03	2479.2	1.0013	2502.3	0.9920	2456.2	1.0107
19	**2482.07**	97.5	0.74	4.29	689,571	1.20E-03	2479.9	1.0009	2502.4	0.9919	2456.8	1.0103
20	**2482.82**	97.5	0.74	4.29	689,780	1.20E-03	2479.7	1.0013	2501.8	0.9924	2457.4	1.0104
21	**10258.07**	97.3	0.74	17.73	2,843,931	5.93E-04	10253.6	1.0004	10343.9	0.9917	10159.0	1.0098
22	**10254.23**	97.3	0.74	17.72	2,842,866	5.93E-04	10249.2	1.0005	10336.7	0.9920	10160.5	1.0092
23	**10253.55**	97.3	0.74	17.72	2,842,678	5.93E-04	10243.4	1.0010	10333.4	0.9923	10153.6	1.0098
24	**10254.26**	97.3	0.74	17.72	2,842,875	5.93E-04	10244.9	1.0009	10334.4	0.9922	10154.2	1.0099
25	**10253.16**	97.3	0.74	17.72	2,842,570	5.93E-04	10253.2	1.0000	10343.2	0.9913	10161.8	1.0090

CAM 21g - Test u1-b1
Date 2008/1/23
ID 15.375
Units 63094.578

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	16985.3	94.8	0.76	29.35	4,586,286	4.67E-04	16975.0	1.0006	17011.1	0.9985	16945.1	1.0024
2	16965.6	94.8	0.76	29.32	4,580,966	4.67E-04	16948.7	1.0010	16981.2	0.9991	16914.5	1.0030
3	16977.4	94.7	0.76	29.34	4,579,286	4.67E-04	16959.3	1.0011	16994.1	0.9990	16925.3	1.0031
4	16956.3	94.6	0.76	29.30	4,568,738	4.68E-04	16942.4	1.0008	16977.1	0.9988	16903.3	1.0031
5	16960.1	94.6	0.76	29.31	4,569,762	4.68E-04	16927.7	1.0019	16963.2	0.9998	16892.5	1.0040
6	6844.7	95.0	0.76	11.83	1,852,086	7.35E-04	6836.0	1.0013	6852.8	0.9988	6817.6	1.0040
7	6843.6	95.0	0.76	11.83	1,851,807	7.35E-04	6836.1	1.0011	6856.3	0.9982	6815.9	1.0041
8	6842.6	95.0	0.76	11.83	1,851,520	7.35E-04	6834.4	1.0012	6852.1	0.9986	6814.1	1.0042
9	6842.8	95.0	0.76	11.83	1,851,571	7.35E-04	6834.6	1.0012	6852.5	0.9986	6815.2	1.0040
10	6839.0	95.0	0.76	11.82	1,850,551	7.35E-04	6833.3	1.0008	6851.3	0.9982	6815.4	1.0035
11	13793.40	94.8	0.76	23.84	3,724,425	5.18E-04	13780.9	1.0009	13805.0	0.9992	13751.5	1.0030
12	13788.20	94.8	0.76	23.83	3,723,021	5.18E-04	13769.0	1.0014	13806.0	0.9987	13733.5	1.0040
13	13794.40	94.8	0.76	23.84	3,724,695	5.18E-04	13776.2	1.0013	13806.5	0.9991	13744.9	1.0036
14	13785.90	94.8	0.76	23.82	3,722,400	5.18E-04	13768.2	1.0013	13793.3	0.9995	13742.9	1.0031
15	13789.80	94.9	0.76	23.83	3,727,408	5.18E-04	13773.1	1.0012	13797.4	0.9994	13746.9	1.0031
16	2534.46	95.2	0.76	4.38	687,253	1.21E-03	2531.6	1.0011	2535.6	0.9996	2527.0	1.0029
17	2533.45	95.2	0.76	4.38	686,979	1.21E-03	2531.8	1.0007	2536.7	0.9987	2526.5	1.0028
18	2532.78	95.2	0.76	4.38	686,797	1.21E-03	2531.3	1.0006	2535.8	0.9988	2526.5	1.0025
19	2534.21	95.2	0.76	4.38	687,185	1.21E-03	2531.7	1.0010	2535.3	0.9996	2528.0	1.0025
20	2535.99	95.2	0.76	4.38	687,667	1.21E-03	2532.9	1.0012	2537.4	0.9994	2527.9	1.0032
21	10264.60	95.0	0.76	17.74	2,777,486	6.00E-04	10253.3	1.0011	10276.0	0.9989	10229.5	1.0034
22	10264.60	95.0	0.76	17.74	2,777,486	6.00E-04	10252.2	1.0012	10273.2	0.9992	10229.4	1.0034
23	10264.70	95.0	0.76	17.74	2,777,513	6.00E-04	10255.0	1.0009	10276.3	0.9989	10231.5	1.0032
24	10262.50	95.0	0.76	17.74	2,776,918	6.00E-04	10248.7	1.0013	10269.7	0.9993	10226.2	1.0035
25	10267.10	95.0	0.76	17.74	2,778,162	6.00E-04	10254.1	1.0013	10274.9	0.9992	10233.2	1.0033

CAM 21h - Test u1-b2

Date	**2008/1/23**
ID	**15.375**
Units	**63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**16868.3**	94.8	0.76	29.15	4,554,694	4.69E-04	16835.4	1.0020	16867.3	1.0001	16817.7	1.0030
2	**16885.6**	94.8	0.76	29.18	4,559,365	4.68E-04	16856.2	1.0017	16880.0	1.0003	16829.8	1.0033
3	**16834.3**	94.8	0.76	29.09	4,545,513	4.69E-04	16815.5	1.0011	16835.7	0.9999	16788.7	1.0027
4	**16848.4**	94.8	0.76	29.12	4,549,321	4.69E-04	16817.5	1.0018	16845.3	1.0002	16790.5	1.0034
5	**16840.9**	94.9	0.76	29.10	4,552,126	4.69E-04	16812.3	1.0017	16839.2	1.0001	16777.1	1.0038
6	**6521.0**	95.3	0.76	11.27	1,770,142	7.52E-04	6513.4	1.0012	6522.8	0.9997	6502.5	1.0029
7	**6521.8**	95.3	0.76	11.27	1,770,353	7.52E-04	6512.7	1.0014	6522.7	0.9999	6500.7	1.0033
8	**6522.2**	95.3	0.76	11.27	1,770,448	7.52E-04	6514.7	1.0011	6524.5	0.9996	6502.5	1.0030
9	**6522.3**	95.3	0.76	11.27	1,770,489	7.52E-04	6512.0	1.0016	6522.9	0.9999	6499.9	1.0035
10	**6526.1**	95.3	0.76	11.28	1,771,526	7.51E-04	6515.7	1.0016	6526.4	1.0000	6505.4	1.0032
11	**13768.22**	95.1	0.76	23.79	3,729,480	5.18E-04	13759.0	1.0007	13772.9	0.9997	13737.8	1.0022
12	**13762.28**	95.1	0.76	23.78	3,727,871	5.18E-04	13749.3	1.0009	13769.6	0.9995	13728.1	1.0025
13	**13754.88**	95.1	0.76	23.77	3,725,866	5.18E-04	13734.9	1.0015	13756.6	0.9999	13712.9	1.0031
14	**13752.99**	95.2	0.76	23.77	3,729,306	5.18E-04	13748.2	1.0003	13771.6	0.9986	13715.9	1.0027
15	**13757.05**	95.2	0.76	23.77	3,730,407	5.18E-04	13744.5	1.0009	13764.1	0.9995	13718.5	1.0028
16	**2506.96**	95.5	0.76	4.33	681,959	1.21E-03	2503.6	1.0013	2503.3	1.0014	2503.6	1.0013
17	**2509.11**	95.5	0.76	4.34	682,544	1.21E-03	2505.7	1.0014	2506.0	1.0012	2505.2	1.0016
18	**2507.00**	95.5	0.76	4.33	681,970	1.21E-03	2504.6	1.0010	2504.6	1.0010	2504.3	1.0011
19	**2504.99**	95.5	0.76	4.33	681,423	1.21E-03	2502.7	1.0009	2502.6	1.0010	2502.6	1.0009
20	**2506.62**	95.5	0.76	4.33	681,867	1.21E-03	2503.2	1.0014	2504.2	1.0010	2502.0	1.0018
21	**10252.16**	95.3	0.76	17.72	2,782,957	5.99E-04	10233.9	1.0018	10248.3	1.0004	10217.2	1.0034
22	**10259.21**	95.3	0.76	17.73	2,784,871	5.99E-04	10242.4	1.0016	10260.2	0.9999	10224.6	1.0034
23	**10254.22**	95.3	0.76	17.72	2,783,517	5.99E-04	10239.4	1.0014	10260.1	0.9994	10216.6	1.0037
24	**10254.10**	95.3	0.76	17.72	2,783,484	5.99E-04	10235.9	1.0018	10251.6	1.0002	10220.2	1.0033
25	**10256.15**	95.3	0.76	17.72	2,784,040	5.99E-04	10237.9	1.0018	10254.2	1.0002	10218.9	1.0036

CAM 21i - Test u1-b3
Date 2008/1/24
ID 15.375
Units 63094.578

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**16378.5**	94.7	0.76	28.31	4,417,746	4.76E-04	16342.1	1.0022	16382.6	0.9997	16302.9	1.0046
2	**16322.0**	94.7	0.76	28.21	4,403,546	4.77E-04	16312.3	1.0006	16349.3	0.9983	16268.1	1.0033
3	**16363.4**	94.7	0.76	28.28	4,413,673	4.76E-04	16346.0	1.0011	16384.4	0.9987	16301.4	1.0038
4	**16357.2**	94.7	0.76	28.27	4,412,009	4.76E-04	16336.1	1.0013	16374.4	0.9990	16295.4	1.0038
5	**16335.5**	94.8	0.76	28.23	4,410,830	4.76E-04	16322.1	1.0008	16357.2	0.9987	16278.4	1.0035
6	**6839.1**	95.1	0.76	11.82	1,852,551	7.35E-04	6825.5	1.0020	6841.6	0.9996	6807.1	1.0047
7	**6838.3**	95.1	0.76	11.82	1,852,331	7.35E-04	6827.8	1.0015	6844.7	0.9991	6809.2	1.0043
8	**6833.9**	95.2	0.76	11.81	1,853,106	7.35E-04	6821.1	1.0019	6839.0	0.9993	6801.8	1.0047
9	**6833.2**	95.2	0.76	11.81	1,852,900	7.35E-04	6819.3	1.0020	6837.2	0.9994	6800.7	1.0048
10	**6832.0**	95.2	0.76	11.81	1,852,577	7.35E-04	6820.6	1.0017	6837.6	0.9992	6801.8	1.0044
11	**13765.80**	95.0	0.76	23.79	3,724,871	5.18E-04	13750.8	1.0011	13776.0	0.9993	13724.5	1.0030
12	**13774.90**	95.0	0.76	23.81	3,727,334	5.18E-04	13754.5	1.0015	13783.3	0.9994	13724.6	1.0037
13	**13760.60**	95.0	0.76	23.78	3,723,464	5.18E-04	13733.4	1.0020	13766.6	0.9996	13701.0	1.0044
14	**13754.80**	95.0	0.76	23.77	3,721,895	5.18E-04	13733.9	1.0015	13756.1	0.9999	13701.2	1.0039
15	**13762.00**	95.0	0.76	23.78	3,725,639	5.18E-04	13742.4	1.0014	13769.8	0.9994	13711.8	1.0037
16	**10302.50**	95.2	0.76	17.80	2,793,660	5.98E-04	10285.2	1.0017	10305.1	0.9997	10263.4	1.0038
17	**10292.90**	95.2	0.76	17.79	2,791,057	5.99E-04	10276.8	1.0016	10300.5	0.9993	10250.6	1.0041
18	**10296.70**	95.2	0.76	17.79	2,792,087	5.98E-04	10282.7	1.0014	10306.3	0.9991	10256.6	1.0039
19	**10294.20**	95.2	0.76	17.79	2,791,409	5.99E-04	10278.3	1.0015	10300.2	0.9994	10254.0	1.0039
20	**10292.70**	95.3	0.76	17.79	2,793,962	5.98E-04	10275.6	1.0017	10299.7	0.9993	10252.2	1.0040

CAM 21j - Test u1-b4

Date	**2008/1/24**
ID	**15.375**
Units	**63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMCheck Paths 5-8	MF Plane B
1	**13227.6**	95.4	0.76	22.86	3,594,449	5.27E-04	13235.1	0.9994	13269.6	0.9968	13199.4	1.0021
2	**13214.7**	95.4	0.76	22.84	3,590,943	5.28E-04	13218.5	0.9997	13247.3	0.9975	13187.4	1.0021
3	**13223.0**	95.4	0.76	22.85	3,593,199	5.28E-04	13222.5	1.0000	13253.2	0.9977	13189.6	1.0025
4	**13201.0**	95.5	0.76	22.81	3,590,387	5.28E-04	13206.8	0.9996	13228.7	0.9979	13182.5	1.0014
5	**13215.9**	95.5	0.76	22.84	3,594,382	5.27E-04	13221.0	0.9996	13251.3	0.9973	13189.1	1.0020
6	**6500.7**	95.4	0.76	11.23	1,766,485	7.52E-04	6491.7	1.0014	6507.4	0.9990	6474.7	1.0040
7	**6493.9**	95.4	0.76	11.22	1,765,073	7.53E-04	6485.9	1.0012	6498.5	0.9993	6472.5	1.0033
8	**6490.8**	95.5	0.76	11.22	1,765,664	7.53E-04	6485.2	1.0009	6498.6	0.9988	6471.0	1.0031
9	**6488.0**	95.5	0.76	11.21	1,764,918	7.53E-04	6478.9	1.0014	6494.1	0.9991	6463.1	1.0039
10	**6489.1**	95.5	0.76	11.21	1,765,212	7.53E-04	6483.1	1.0009	6493.6	0.9993	6472.1	1.0026
11	**10245.60**	95.3	0.76	17.71	2,781,177	6.00E-04	10239.6	1.0006	10261.5	0.9985	10216.8	1.0028
12	**10245.30**	95.3	0.76	17.71	2,781,095	6.00E-04	10238.2	1.0007	10250.8	0.9995	10226.7	1.0018
13	**10244.90**	95.3	0.76	17.71	2,782,250	6.00E-04	10236.3	1.0008	10251.6	0.9993	10219.4	1.0025
14	**10245.80**	95.4	0.76	17.71	2,784,179	5.99E-04	10234.5	1.0011	10252.2	0.9994	10214.5	1.0031
15	**10244.40**	95.4	0.76	17.70	2,783,798	5.99E-04	10232.8	1.0011	10249.7	0.9995	10216.2	1.0028

CAM 21k - Test u2-b1
Date **2008/1/24**
ID **15.375**
Units **63094.578**

Test No.	ARL (gpm)	LEFM Temp (degF)	Viscosity (cSt)	Velocity (fps)	Reynolds Number (x106)	1/sqrt(Re)	LEFM CheckPlus	MF CheckPlus	LEFMCheck Paths 1-4	MF Plane A	LEFMChec k Paths 5-8	MF Plane B
1	**16910.5**	95.3	0.76	29.22	4,590,369	4.67E-04	16856.3	1.0032	16858.5	1.0031	16848.9	1.0037
2	**16922.9**	95.2	0.76	29.25	4,588,859	4.67E-04	16859.4	1.0038	16856.1	1.0040	16858.8	1.0038
3	**16915.4**	95.2	0.76	29.23	4,584,664	4.67E-04	16854.1	1.0036	16847.5	1.0040	16852.2	1.0037
4	**16909.7**	95.1	0.76	29.22	4,580,431	4.67E-04	16861.0	1.0029	16860.4	1.0029	16854.6	1.0033
5	**16913.6**	95.1	0.76	29.23	4,581,482	4.67E-04	16855.8	1.0034	16858.1	1.0033	16850.9	1.0037
6	**6558.0**	95.5	0.76	11.33	1,783,941	7.49E-04	6534.2	1.0036	6535.7	1.0034	6531.2	1.0041
7	**6555.5**	95.5	0.76	11.33	1,783,261	7.49E-04	6532.5	1.0035	6536.9	1.0028	6527.3	1.0043
8	**6552.2**	95.5	0.76	11.32	1,782,371	7.49E-04	6530.5	1.0033	6535.4	1.0026	6525.8	1.0040
9	**6554.8**	95.5	0.76	11.33	1,783,081	7.49E-04	6532.3	1.0035	6535.0	1.0030	6529.9	1.0038
10	**6555.7**	95.5	0.76	11.33	1,783,334	7.49E-04	6533.1	1.0035	6539.5	1.0025	6527.2	1.0044
11	**13865.11**	95.3	0.76	23.96	3,763,696	5.15E-04	13814.8	1.0036	13820.8	1.0032	13809.0	1.0041
12	**13863.40**	95.3	0.76	23.96	3,763,231	5.15E-04	13804.5	1.0043	13804.8	1.0042	13802.6	1.0044
13	**13863.85**	95.3	0.76	23.96	3,763,354	5.15E-04	13813.5	1.0036	13809.9	1.0039	13813.2	1.0037
14	**13830.82**	95.4	0.76	23.90	3,756,558	5.16E-04	13794.6	1.0026	13786.7	1.0032	13790.0	1.0030
15	**13862.20**	95.4	0.76	23.96	3,766,894	5.15E-04	13816.1	1.0033	13813.9	1.0035	13814.3	1.0035
16	**2538.65**	95.7	0.75	4.39	692,043	1.20E-03	2531.1	1.0030	2534.0	1.0018	2526.9	1.0047
17	**2533.71**	95.7	0.75	4.38	690,696	1.20E-03	2523.8	1.0039	2525.0	1.0034	2521.6	1.0048
18	**2532.60**	95.7	0.75	4.38	690,394	1.20E-03	2523.7	1.0035	2526.2	1.0025	2520.2	1.0049
19	**2534.59**	95.7	0.75	4.38	690,936	1.20E-03	2524.5	1.0040	2528.3	1.0025	2520.5	1.0056
20	**2537.25**	95.7	0.75	4.38	691,661	1.20E-03	2528.0	1.0036	2531.0	1.0025	2524.7	1.0050
21	**10264.28**	95.5	0.76	17.74	2,792,154	5.98E-04	10227.1	1.0036	10231.8	1.0032	10220.1	1.0043
22	**10255.71**	95.5	0.76	17.72	2,789,824	5.99E-04	10220.0	1.0035	10226.8	1.0028	10212.9	1.0042
23	**10259.37**	95.5	0.76	17.73	2,790,819	5.99E-04	10222.5	1.0036	10227.1	1.0032	10216.9	1.0042
24	**10256.30**	95.5	0.76	17.72	2,789,984	5.99E-04	10219.6	1.0036	10220.4	1.0035	10217.0	1.0038
25	**10252.07**	95.5	0.76	17.72	2,788,834	5.99E-04	10219.4	1.0032	10222.8	1.0029	10212.9	1.0038