行政院所屬各機關因公出國人員出國報告書
（出國類別： 研 習 ）

赴日本京都大學及美國橡樹嶺國家實驗室研習研究用反應爐試運轉、運轉維護及運轉規劃等相關事宜

服務機關：行政院原子能委員會核能研究所
出 國 人 職 稱：簡任副研究員
姓 名：石志堅

出國地點：日本、美國

出國期間： 89 年 7 月 1 日至 89 年 12 月 31 日

報告日期： 90 年 2 月 28 日

摘 要

職此次奉派赴日本京都大學原子爐實驗所(Kyoto University Research Reactor Institute, KURRI)及美國橡樹嶺國家實驗室(Oak Ridge National Laboratory, ORNL)之高通率同位素核子反應器(High Flux Isotope Reactor，HFIR)研習，主要工作除討論學習核子反應器相關之運轉維修技術如啟爐、停爐、大修等實務外，另外亦對試運轉，首次啟爐，中子源與中子量測技術，緊急應變及人員疏散計畫，反應器大修與測試計畫，核子反應器人力組織等做相關之涉獵，另亦參與京都大學冷中子源實驗設施之啟動運轉及硼中子捕捉治療 (BNCT)相關技術之討論。

橡樹嶺國家實驗室高中子通量同位素反應器及京都大學原子爐實驗所均為世界知名之研究用反應器，預計此行對目前 TRR-II 專案計畫內運轉維修工作之推動如主冷卻水系統， 廠房通風系統， 控制保護系統及實驗設施等運轉限制條件訂定，緊急應變計畫之擬定，運轉維修人員架構訂定，試運轉計畫之擬定等頗有助益，對未來 TRR-II 核子反應器之冷熱試車及運轉維修等工作亦有極大之幫助。

目 錄

一、目的

橡樹嶺國家實驗室(Oak Ridge National Laboratory, ORNL)屬於美國能源部委託田納西大學及貝泰能源公司經營之國家實驗室, 其高中子通量同位素反應器(High Flux Isotope Reactor , HFIR)為知名之世界最高中子通量(2.3x10^{15} n /sec.cm^2)研究用反應器, 位於田納西州橡樹嶺市, 現有員工 200 餘人(含支援人力如保健物理, 實驗設施技術等 60 人),其編制為一個直屬橡樹嶺國家實驗室的獨立研究用反應器組(Research Reactor Division, RRD), 其下包括運轉部門,維護部門,設計部門, 計畫與訓練部門及行政支援部門等,每年約有 200 名來自於全國以及國外之研究人員進行各項中子實驗. 該原子爐主要任務為中子散射實驗並生產同位素如 Pu-238, Cf-252 供工業,醫學,及學術界使用.職此次赴 ORNL 研習反應器運轉維修專題，適逢 HFIR 大修更換鈹反射體，冷卻水塔及若干電力系統、熱交換器裝備之更新，故對研究用反應器之維修程序、維修準則與法規亦有參與；期能提供 TRR-II 計畫日後運轉維修工作之參考。

日本京都大學原子爐實驗所校區(Kyoto University Research Reactor Institute, KURRI)位於日本大阪府泉南郡熊取市，現有員工 200 餘人，包括 21 位教授，24 位助教授；每年約有 8000 名來自於日本全國，以至國外大學之物理、化學、生物醫學、藥學、工程、農業、環境等自然科學領域之研究人員，故該原子爐實驗所係日本全國共同利用之研究所。

京都大學原子爐實驗所設有中子科學研究部，應用原子核科學研究部，核工基礎研究部，應用原子核

科學研究部，放射線生命科學研究部，原子爐應用研究部及原子爐醫療基礎研究部等各研究部門。所長之下另設一直屬單位為原子爐營運安全管理部，負責原子爐之計畫管理，安全運轉，核燃料管理及實驗設備管理等事宜。

職此次奉派赴日本京都大學原子爐實驗所 KURRI 及美國橡樹嶺國家實驗室之高通率核子反應器 HFIR 研習，主要工作除討論學習核子反應器相關之運轉維修技術如啟爐、停爐、大修實務外，另外亦對試運轉，首次啟爐，中子源與中子量測技術，緊急應變及人員疏散計畫，反應器大修與測試計畫，核子反應器人力組織等做一定程度之涉獵，另亦參與京都大學冷中子源實驗設施之啟動運轉及硼中子捕捉治療(BNCT)相關技術之討論。預計此行對目前 TRR-II 專案計畫內運轉維修工作之推動如運轉限制條件訂定，緊急應變計畫之擬定，運轉維修人員架構訂定等頗有助益，對未來 TRR-II 核子反應器之運轉維修及冷熱試車等工作亦有極大之幫助。

二、過程

(一) 行程

時間	地點	內容
7/1~7/31	京都	赴京都大學原子力實驗所 KURRI 研習研究用反應器運轉維修、試運轉、運轉規畫等相關技術
8/1~12/31	田納西橡樹嶺市	赴美國橡樹嶺國家實驗室 ORNL 研討學習研究用反應器運轉維修、緊急應變計畫、首次啟爐中子源等相關技術並拜訪美國國家標準局核子反應器 NBSR

訪問機構及人員

KURRI 三島嘉一郎(教授)
河合武(教授)
石原信二(工程師)
藤田薰顯(教授)
古林徹(教授)

ORNL Dr. Gary Rothenberger (Head)
Dr. George Flanagan (Deputy Head)
Mr. Ron Crone (Operation Department Manager)
Mr. David Blanchard (Emergency Response Manager)
Dr. Rothrock (Reactor Physics scientist)

NBSR Dr. Mike Rowe (Director of NBSR)
Dr. Raby (Head of Operation & Engineering Division)

(二)參訪紀要

日本京都大學原子爐實驗所校區(Kyoto University Research Reactor Institute, KURRI)位於日本大阪府泉南郡熊取市，現有員工 200 餘人，包括 21 位教授，24 位助教授；每年約有 8000 名來自於日本全國，以至國外大學之物理、化學、生物醫學、藥學、工程、農業、環境等自然科學領域之研究人員，故該原子爐實驗所係日本全國共同利用之研究所；現任所長為井上信教授，係該所第八任所長。原子爐實驗所人力組織架構如附圖一.

京都大學原子爐實驗所有位儀控專家石原信二博士(Dr. Ishihara)當年負責 JRR-3M 及 KUR 控制棒驅動系統(Control Rod Drive Mechanism, CRDM)之設計，同時也是 KUR 之 BNCT 與 CNS 儀控系統設計者。

京都大學屬教育部較具學術氣息，且其原子爐實驗所已運轉三十多年，在日本研究用反應器界首屈一指，教授水準已屬世界知名，如冷中子源設施及冷中子實驗之河合武教授，目前為國際原子能總署(IAEA)冷中子源小組審查委員；三島嘉一郎教授(Prof. Mishima)為國際知名熱流實驗專家及研討會分組主席，TRR-II 爐心 DNBR 熱流驗證即應用 Mishima Correlation 驗證。

職於京都大學原子爐實驗所參與實習下列工作:

1. KUR 反應器起爐程序(89/7/1 -89/7/31)
2. KUR 反應器停爐程序(89/7/1 -89/7/31)
3. KUR 反應器樣品棒操作(89/7/1 -89/7/31)
4. KUR 反應器燃料棒操作(89/7/1 -89/7/31)
5. KUR 反應器冷中子源設施操作(89/7/21 -89/7/31)

職於京都大學原子爐實驗所參與討論下列工作:

1. KUR 反應器首次起爐中子源及中子量測技術(89/7/1 -89/7/31)
2. KUR 反應器試運轉技術(89/7/1 -89/7/31)
3. KUR 反應器緊急應變計畫(89/7/1 -89/7/31)
4. KUR 反應器人力組織(89/7/1 -89/7/31)

職於京都大學原子爐實驗所參與實習期間, 除將運轉維修心得記錄於筆記外, 另外攜回 KUR 初期特性試驗, KUR 原子爐實驗所保安規定, JRR-3M 燃料爐心特性試驗等資料存本所圖書館.

橡樹嶺國家實驗室高中子通量同位素反應器(HFIR) 由美國 AEC 於 1959 年 3 月責成橡樹嶺國家實驗室設計，1961 年 6 月開始建造，1965 年 1 月建造完成後進行熱流與機械系統測試，並於 1965 年 8 月 25 日達到初次臨界，其最大熱功率為 100MW，實驗靶區 (Target Region) 最大熱中子通量為 2.3×10^{15}n/sec.cm^{2} 初次臨界後，經逐步提升功率測試 (Power Ascension Test), HFIR 於 1966 年 9 月達額定功率 100MW 運轉。1986 年 11 月，HFIR 研究人員由 Surveillance Program 測試報告發現，其爐心壓力槽受中子照射脆化程度比預測更為嚴重，為維持壓力槽之結構完整性，HFIR 決定停爐兩年半以重新分析評估主冷卻水壓力與壓力槽可承受之熱限，1989 年 4 月獲美國能源部批准，重新啟動於 85MW 運轉迄今。高中子通量同位素反應器現任組長為 Dr. Gary Rothenberger , 副組長為 Dr. George Flanagan. HFIR 反應器人力組織如附圖二 , 三.

職此次赴 ORNL 研習反應器運轉維修專題，適逢 HFIR 大修更換鈹反射體，冷卻水塔及若干電力系統、熱交換器裝備之更新，故對研究用反應器之維修程序、維修準則與法規亦作涉獵；期能提供 TRR-II 計畫日後運轉維修工作之參考。

橡樹嶺國家實驗室對 HFIR 核反應器機密安全工作之維護非常注意,台灣因為李文和間諜案被美國國務院列為敏感國家, 故曾要求職於停留 HFIR 期間簽署一份文件, 對於外國訪問人員, 均不得利用其電腦下載或利用其電腦以電子郵件方式傳送任何有關 HFIR 核子反應器技術信息, 違反規定可處以罰款及監禁.

橡樹嶺國家實驗室要求職於 2000 年 9 月下旬向 HFIR 做 TRR-II 現況簡報,經請示馬副主持人同意, 從 2000 年 4 月向 TRR-II 技術指導委員會(TRC)委員做現況簡報之資料中取出 10 張 TRR-II 一般性介紹透明片, 於 HFIR 經理級會議中報告, 現場有兩位美國能源部官員專程前來聆聽(Dr. Madeline Feltus, DOE office of nuclear energy, science and technology. 及 Mr. Stanley Staten, DOE office of basic energy sciences). 簡報同時職不忘請教現場聆聽人員有關重水中氚濃度之限制問題, 因 HFIR 係輕水冷卻與緩和, 沒有重水緩和劑系統故無人可以答覆, 但當場美國能源部官員 Mr. Stanley Staten 提出他在美國布魯克海文國家實驗室 HFBR 反應器及美國國家標準局 NBSR 核子反應器的經驗, HFBR 及 NIST 僅由其重水系統中取出老的重水裝桶運往加拿大處理, 而另外以新鮮重水加入重水緩和劑系統中, 以達到解決降低重水中氚濃度之問題.

職於橡樹嶺國家實驗室參與實習下列工作:

1. HFIR 反應器起爐程序(89/8 - 89/9)
2. HFIR 反應器停爐程序(89/8 - 89/9)
3. HFIR 反應器大修作業(89/10 - 89/12)
4. HFIR 反應器燃料棒操作(89/8 - 89/9)

職於橡樹嶺國家實驗室參與討論下列工作:

1. HFIR 反應器首次起爐中子源及中子量測技術(89/10 - 89/12)
2. HFIR 反應器試運轉技術(89/10 - 89/12)
3. HFIR 反應器 ISI 測試計畫(89/10 - 89/12)
4. HFIR 反應器緊急應變及人員疏散計畫(89/10 - 89/12)
5. HFIR 反應器人力組織(89/10 - 89/12)

職於橡樹嶺國家實驗室實習期間, 除將運轉維修心得記錄於筆記本外, 另外攜回 HFIR SAR, HFIR 運轉程序書, HFIR 維修 Guideline, HFIR 運轉限制條件等資料存本所圖書館.

(三)心得

職由研習 HFIR 安全分析報告顯示,當年 HFIR 由 1959 年開始設計到 1966 年 9 月額定功率 100MW 運轉共費時約 7.5 年，與 TRR-II 計畫時程 7 年相當; HFIR 建造完成後進行熱流與機械系統冷試車測試共費時約 7 個月,與 TRR-II 計畫運轉規畫 6 個月相當.

因為鋁合金 5000 系列有較多的鎂含量，焊接性比鋁合金 6000 系列要好；但對於鎂含量高的鋁合金 5000 系列，因中子累積通量（Neutron fluence）越多越易造成鎂 Deposition 腫脹變形，日本京都大學原子爐功率只有 5MW，緩速腔處最大熱中子通量僅 $1x10^{13}$ n /sec.㎝^{2}，照射後緩速腔，傳送管，冷凝器沒有腫脹變形之顧慮,故其材質使用鋁合金 5000 系列之 Al-5052；但是核能研究所 TRR-II 功率 20MW，最大熱中子通量高達 $3x10^{14}$ n /sec.㎝^{2}，緩速腔照射後有腫脹變形之顧慮，1999 年 5 月經 TRR-II 計畫結構小組完成使用壽命年限評估並呈報計畫決定：TRR-II 冷中子源緩速腔使用鋁合金 6000 系列之 Al 6061-T6．針對此重要議題之驗證，職與 HFIR 冷中子源設施負責人 Dr. D. Selby 及 Dr. Bill Hill 討論緩速腔材質使用年限評估及材料選擇之問題時，Dr. Selby 稱因 HFIR 最大熱中子通量高達 $2.3x10^{15}$ n /sec.㎝^{2}，緩速腔若使用鋁合金 5000 系列則有腫脹變形之顧慮，所以 HFIR 冷中子源緩速腔，傳送管，冷凝器均使用鋁合金 6000 系列.此結論與 TRR-II 計畫於冷中子源基本設計之初，TRR-II 結構小組早在 1999 年 5 月即針對鋁合金之輻射特性，並依照 1980

年 Dr. Farrell 於 ORNL HFIR 對鋁合金 5000 系列與 1990 年 Dr. John Weeks 於 BNL HFBR 對鋁合金 6000 系列之研究實驗報告，同時考量 TRR-II 最大熱中子通量特性，對 TRR-II 冷中子源緩速腔做 Sizing Calculation 評估使用壽命與應力分析後,作成選擇鋁合金 6000 系列為緩速腔，傳送管，冷凝器之材料互相吻合，從而取得驗證與信心.至於破壞力學分析及流沖振動分析，TRR-II 冷中子源緩速腔則尚未分析.

HFIR 用過後燃料運送至美國南卡羅萊納州 Savannah River 實驗室作再處理.HFIR 運轉 35 年從未發生燃料破裂事件.ORNL ORR(Oak Ridge Research Reactor)反應器為世界上第一個使用 U_3Si_2-Al 燃料之研究用反應器(TRR-II 亦採用此種 U_3Si_2-Al 燃料)．註：{職與 HFIR 資深核燃料專家 Mr. Rodney Knight（已年屆 78 高齡，HFIR 仍不讓他退休，因為在 HFIR 其核燃料專業無人可以取代)討論 U_3Si_2-Al 燃料，亦提及 TRR-II 準備與 CERCA 及 B&W 兩家核燃料公司接觸，並詢問他對 U_3Si_2-Al 燃料之意見，其稱截至目前為止 U_3Si_2-Al 燃料尚無破裂記錄，係屬於穩定性高的燃料；再詢問他那家較好，則答覆 HFIR 與 CERCA 及 B&W 兩家公司均有合約，但各有缺點.}

反應器在高功率運轉時,為避免 Fission Chamber 達到飽和而損壞,HFIR 高中子通量同位素反應器於 10% of full power 約 10,000 CPS 將其 Fission Chamber 以伺服馬達抽離爐心高中子通率區.註：{職

返國後,已於參加儀控界面會議時提出 TRR-II 中子量測儀器之 5 個 Fission Chambers (3 for RPS and 2 for RPCS)設計，是否已考量此重點之議題.}

HFIR primary coolant 之 Flux-to-Flow Ratio 為 1.36 at 16,000 gpm; 2.4 at 1500 gpm at operating mode 1. 註: {TRR-II primary coolant 為 constant flow,沒有 Allowable Power vs Flow map to keep TRR-II in the safe operating range 之問題}

當 HFIR 廠外電源喪失時,緊急柴油機有兩種不同之啟動方式:

No 1 diesel is an electric start diesel supplied with its own battery and charger. No 2 diesel is air start and has its own air receiver and compressor. 註: {此為 HFIR 避免 Common mode failure 而設計，建議 TRR-II 緊急柴油機考量此點}

此外，HFIR 緊急電源系統尚有兩台輔助緊急柴油機 (Auxiliary Emergency Power Generators, AEPG's)，其設計目的為降低電瓶組正常運轉維修負荷.

註:{此點係 HFIR 為維持電瓶組基本容量,從而降低電瓶組正常運轉維修負荷而設計；當廠外電源喪失時，又可適時啟動該輔助緊急柴油機以增加緊急直流電力供應；與核四廠之 Swing Diesel Generator 設計相當. TRR-II 緊急電源系統沒有此項設計.}

HFIR 主控制室屬於清潔區,以獨立之風扇及氣門維持稍高之正壓力,TRR-II 主控制室即為此項設計.

在首次臨界啟爐程序方面，HFIR 於 1965 年使用三組 Fission Chambers 並以 Antimony Sb-124 作為中子源,藉(r , n) Reaction 完成中子量測達到臨界, 註: {針對此議題職與 HFIR Dr. Dick Rothrock 討論 TRR-II project 在首次臨界啟爐程序方面應注意之事項，Dr. Dick Rothrock 建議：因為 TRR-II 沒有 Beryllium 反射體，故可以考量以 Cf-252 or (Am + Be) 當作首次臨界啟爐之中子源，首次臨界啟爐之中子強度必須大於 10^6 neutrons/sec，並且建議中子量測儀器必須儘量靠近爐心以確保其靈敏度.
Dr. Dick Rothrock 同時建議 TRR-II 最好向國內大學或研究所借用首次臨界啟爐之中子源及兩個高靈敏度(High Sensitivity，Counting Rate > 10 ~ 50 neutrons/sec) 之中子量測 Fission Chambers，並且將兩個中子量測 Fission Chambers 儘量靠近爐心以求得更精確之中子 Counting Rate，其優點為 TRR-II 不必以厚重之屏蔽鉛罐來維持此中子源.

京都大學 KUR Dr. Ishihara 建議：由於 BF_3 中子量測儀器之不穩定來自於 Strong Gamma Ray Ionization，但是 BF_3 中子量測儀器之靈敏度為 Fission Chamber 之十倍. 所以在首次臨界啟爐程序方面,京都大學 KUR 同時採用 BF_3 中子量測儀器及 Fission Chamber 中子量測儀器當作首次臨界啟爐之中子 Detector.}

基於 KUR 及 HFIR 之經驗，初步建議 TRR-II 使用 (Am+Be)作為首次臨界啟爐之中子源，並以 BF_3 Neutron Detector 作為中子量測儀器.

在 HFIR 長期停爐後啟爐程序方面,1986 年 11 月，HFIR 研究人員由 Vessel Surveillance Program 測試報告發現，其爐心壓力槽受中子照射脆化程度比預測更為嚴重，為維持壓力槽之結構完整性，HFIR 決定停爐兩年半以重新分析,評估主冷卻水壓力與壓力槽可承受之熱限，1989 年 4 月獲美國能源部批准，重新啟動於 85 MW 運轉.與 HFIR Dr. Rothrock 討論，HFIR 停爐兩年半後於 1989 年 4 月重新啟動，其 Start up 方式與 HFIR 首次臨界啟爐程序不同，因為 Sb-124 之半衰期僅 60 天，當年之中子源 Sb-124 已不能使用. 1989 年 HFIR 使用 Curium-96 作為長期停爐後啟爐之中子源,此點可供 TRR-II 未來運轉參考.

TRR-II 重水槽及爐心通道之鋁合金 Al-6061-T6 輻射腫脹現象，是未來 TRR-II In-Service Inspection Program 之重點，目前結構小組分析 The Maximum Inward Deformation of Core Channel,14 mm Al-6061-S-T62 in Thickness，得知 TRR-II 爐心通道受 40 年之輻射照射腫脹尺寸為 0.0077 mm,小於燃料束及爐心通道內壁之設計間隙 1 mm . 但實際輻射腫脹情況，仍然要靠現場 ISI 檢驗為準. 另外建議 TRR-II 主冷卻水及次冷卻水管路應作 Stress Analysis，管路高應力點作為未來運轉 ISI 之依據，建議本所依 ASME Code 及相關法規，建立 TRR-II 未來自己的 ISI program.

註:{此點為 TRR-II 未來維修檢測工作之重點方向.}. HFIR 對其大型轉動機械如馬達, 幫浦, 風扇等訂定預測保養與診斷計畫, 以永久固定之加速度計(Accelerameter)量測振動值後, 轉換成振動頻譜圖, 做為肇因分析與趨勢分析之依據. 註:{此點 TRR-I 已行之有年,建議 TRR-II 繼續遵循.}

HFIR 緊急計畫區域 (EPZ)分析係遵照:

1). 美國 DOE G 151.1 "Emergency Management Guide", August 1997. ORNL/M-2344/V1,

2). DOE G 151.1" Comprehensive Emergency Management System", August 21,1996.

3). HFIR PRA, D.H.Johnson,et.al.,ORNL/RRD/INT-36/R1.

4). HFIR Safety Analysis Report, ORNL/M-2344, Rev. 2.

5). Emergency Planning Zone Document for ORNL, EPZ-95-1-R1, May 1996

6). DOE-STD-1027.92 "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE order 5480.23, Nuclear Safety Analysis Reports", December 1992.

六種文件要求, 並由 HFIR PRA Level 1 analysis and some of Level 2 analysis 分析結果, 找出機率大於 credibility cutoff of 1.0E-6 per year 且會導致 fuel damage 及 radioactive material release 之各項 Scenarios, 再依照這些 Scenarios 做危害分析後可得到不同邊界之 Significant offsite radiological consequence and their

estimated doses, which are the important source term(No. of Curie, No. of nuclei) inputs to plug into the EPZ analysis model for the analysis of emergency planning zone.
HFIR 依 EPZ analysis model [ISC(3)ST, which is a industrial source code in Environment Protection Agency] to get their EPZ as 12 miles.ORNL got an agreement with Tennessee State government that ORNL can only take care of 5 miles for HFIR EPZ, it's the responsibility of Tennessee State government beyond 5 miles.
註:{TRR-II 目前沒有 PRA 分析結果, SAR 亦未定案, 無法做 TRR-II Hazard Analysis, 亦無法做 TRR-II 之 Emergency Planning Zone 分析.建議 TRR-II 盡早做 PRA 分析以落實 TRR-II 之 Emergency Planning Zone.

HFIR 詳細運轉維修作業及心得請參考附錄一註解部份。

京都大學原子爐由日本日立公司設計建造，其最大熱功率為 5MW，最大熱中子通量為 $3x10^{13}$ n /sec.cm^2，冷中子源緩速腔處中子通量為 $1x10^{13}$ n /sec.cm^2，京都大學於昭和 36 年 (1961) 9 月提出原子爐設置申請，同年 12 月開工；昭和 39 年 6 月 25 日首次臨界運轉成功，同年 8 月輸出功率達 1MW；並於昭和 42 年 7 月其輸出功率達額定功率 5MW 運轉，故其由首次臨界到額定功率 5MW 運轉共費時約

3 年，在 3 年內共計進行安裝實驗設施，申請運轉執照及提升功率等事宜。其由設置申請到額定功率 5MW 運轉共費時約 6 年, TRR-II 整體時程規畫 7 年(包括移爐)應屬合理.

京都大學原子爐實驗所有位儀控專家石原信二博士(Dr. Ishihara)當年負責 JRR-3M 及京都大學原子爐控制棒驅動系統(Control Rod Drive Mechanism, CRDM)之設計製造，同時也是 KUR 之硼中子捕捉(BNCT)與冷中子源儀控系統設計者。建議可將石原博士列為核能研究所之諮詢人才庫內

在硼中子捕捉治療 (Boron Neutron Capture Therapy, BNCT) 領域中, 京都大學原子爐實驗所古林 徹教授(Prof. Cobayashi) 是位資深專家, 古林教授於 1996 年 5 月負責完成 BNCT 設施之設計與建造. 較優於美國 BNCT 療法, 京都大學原子爐實驗所與京都大學醫學院合作, 在硼中子捕捉療法上係以混合中子(Mixed Thermal Neutron and Epi-thermal Neutron)成功地治療了 79 位腦腫瘤(第三期)及皮膚癌患者, 五年存活率達百分比之六十. 古林教授強調 BNCT 設施必須離原子爐爐心越近越好, 熱中子通量必須大於 $3x10^9$ n /sec.cm^2 才能達到預期療效, 故建議目前 TRR-II BNCT 預留空間應參考此一需求。

京都大學原子爐實驗所冷中子源設施(Cold Neutron Source Facility, CNS)屬於中子科學研究部，該所冷中子源設施使用液態氘(Deuterium)做為緩速腔之冷卻劑，原因為氘有較小的散射截面(Scattering Cross Section)，可以容許更大的緩速

腔體積，該所之冷中子源設施緩速腔焊接性比鋁合金 6000 系列要好；但對於鎂含量高的鋁合金 5000 系列，因為中子累積通量越多越易造成鎂 Deposition 腫脹變形，京都大學原子爐功率 5MW，緩速腔處最大熱中子通量為 $1x10^{13}$ n /sec.㎝^{2}，照射後沒有腫脹變形之顧慮；但是核能研究所 TRR-II 功率 20MW，最大熱中子通量高達 $3x10^{14}$ n /sec.㎝^{2}，緩速腔照射後有腫脹變形之顧慮，所以經評估計算 TRR-II 使用鋁合金 6000 系列之 Al 6061-T6，但其焊接性較差.建議將由日後 TRR-II 之檢測計畫補強.

京都大學原子爐運轉模式如下:

燃料更換模式: zero power, primary, secondary pumps & cooling tower fans are OFF; NCV open, 4 shim rods and one regulating rod are in the 24 ㎝ position as the Shutdown margin.

自然循環模式: 0 < Power < 100 Kw, primary, secondary pumps & cooling tower fans are OFF; NCV open, 4 shim rods and one regulating rod are in the bottom position (0 ㎝). But normally, turn on the primary/secondary pumps and cooling tower fans before start up the reactor.

功率運轉模式: 100 Kw <power < 5 Mw, primary, secondary pumps are ON, two CT fans are ON for 100 Kw <power < 1 Mw, three CT fans are ON for 5 Mw. But normally, turn on the primary/secondary pumps during 出力運轉前檢查表(做完更換燃料 or core reconfiguration/低出力

檢查，冷卻水運轉時) before reactor starts up. When in 5 MW operation, 4 shim rods are in the 37 cm position and regulating rod is in 35 cm position. Reactor period is infinite.

三種運轉模式之間有 key 可以相互轉換,將建議 TRR-II 儀控界面參考.

京都大學原子爐全部停爐過程只需 15 分鐘即可完成.

反應器停爐後，要依步驟做停爐點撿，將控制棒驅動機構磁鐵電源鎖匙，Local/DCS 轉換鎖匙，控制電源鎖匙，保護系統控制面盤鎖匙拔出，並將運轉模式鎖匙置於自然循環位置後拔出(共五支鎖匙)，關閉 Recorder，Chart，Start up Monitor 電源，並將 4 shim rods position 升置 4.18cm 位置(將 CRDM 避開爐頂上方 high humidity region)，2 Fission Chamber 自動下降到底，停止主冷卻水 Pump,次冷卻水 Pump 及三台冷卻水塔風扇運轉，自然循環閥自動打開後即完成所有停爐程序.
停爐後僅維持下列設備運轉:

- Spent fuel clean up pump
- Primary clean up pump
- Sweep gas blower
- Cooling tower pump
- Secondary clean up system.

註：京都大學原子爐自然循環閥之設計在若干年前也是手動操作，但目前已完全自動，其原理為停止主冷卻水 Pump 後其出口壓力水頭消失，原先被該出口壓力經一迴路頂上去的閥桿，自由落到定位而產生一

流體通路，造成自然循環閥自動打開，爐底之水向上流動形成爐心自然循環．建議 TRR-II 爐體界面參考．

京都大學原子爐燃料及樣品棒之操作完全由運轉員手動操控而不用吊車,其原因為手動操控手感較為靈活穩定,TRR-II 燃料每根僅 11 Kg, 建議亦可研究比照辦理.

京都大學屬教育部為學術機關, 為求教學相長及節省預算,其博士助理教授均須值班運轉原子爐; 核能研究所博士眾多,建議亦可研究比照辦理,以達核工理論與實務互相結合.

京都大學原子爐實驗所詳細運轉維修作業及心得請參考附錄二。

四. 建議

1. 美國目前能源充足, 雖然在其國內暫停核能電廠之興建, 但在核能研究方面所投入之人力與預算仍然遠超過其他核能先進國家, 橡樹嶺國家實驗室目前最大之核能研究計畫為 Neutron Spallation Source Project, HFIR 核反應器升級為第二大之核能研究計畫. 同時, 美國參議員亦非常重視俗稱原子能市(Atomic City)之田納西州橡樹嶺市之核能研究發展, 九月來訪時即同意未來五年將特別補助兩億美元給橡樹嶺國家實驗室. 建議國內相關單位亦能重視我國之核能研究發展.

2. HFIR 核子反應器運轉維修工作係遵照美國能源部核子設施運轉維修政策 DOE 4330.4B Chapter 11 而定, 值得 TRR-II 運轉維修小組參考; 而其工作控制,協調 管理方式例如每天召開維修會議, 每週召開運轉會議, 每雙週召開經理級(課長)會議, 尤其值得借鏡.

3. 建議未來 TRR-II 運轉後, 在降低重水中氚濃度之問題方面, 能借重美國研究用反應器 HFBR 及 NBSR 之經驗, 僅由 TRR-II 重水系統中取出老的重水, 而另外以新鮮重水加入重水緩和劑系統中, 以達到解決降低重水中氚濃度之問題.

4. 京都大學原子爐實驗所有位儀控專家石原信二博士 (Dr. Ishihara) 當年負責 JRR-3M 及 KUR 控制棒驅動系統 (Control Rod Drive Mechanism,

CRDM)之設計, 同時也是 KUR 之 BNCT 與 CNS 儀控系統設計者,TRR-II 控制棒驅動系統設計負責人宋永作博士曾於 1999 年赴 KUR 向石原信二博士訪問, 因日本 JRR-3M 為核能研究所 TRR-II 參考廠, 而控制棒驅動系統又屬重要安全系統, 建議可將石原博士列為核能研究所之諮詢人才庫內.

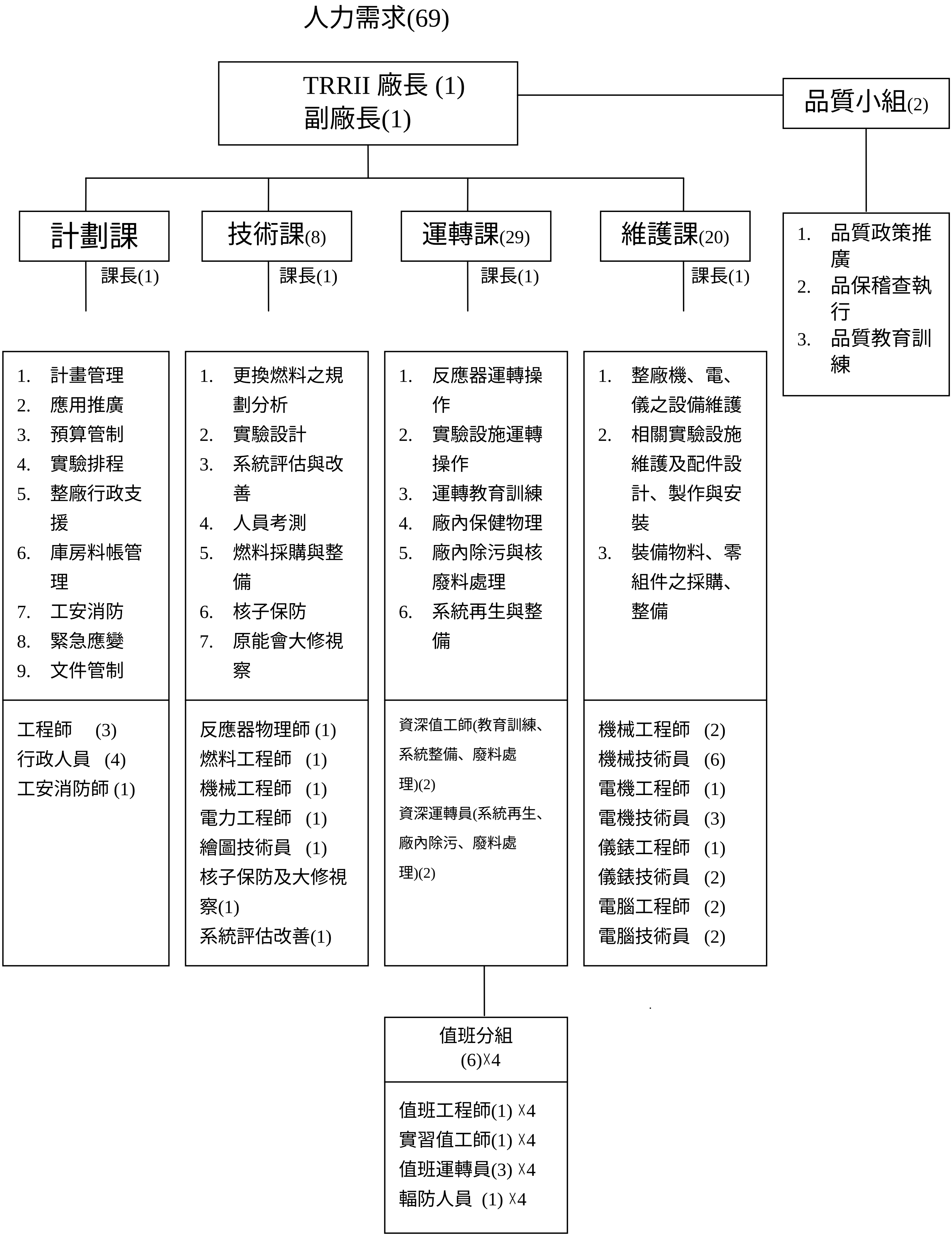
5. 因政治原因台灣與日本官方科技廳原子力研究所(JAERI)不易接觸, 但京都大學屬教育部較具學術氣息, 且其原子爐實驗所已運轉三十多年,在日本研究用反應器界首屈一指, 教授水準已屬世界知名, 如冷中子源設施及冷中子實驗之河合武教授, 目前為國際原子能總署(IAEA)冷中子源小組審查委員;三島嘉一郎教授(Prof. Mishima)為國際知名熱流實驗專家及研討會分組主席, TRR-II 爐心 DNBR 熱流驗證即應用 Mishima Correlation 公式, 大陸過去三年曾有包括西安交通大學, 北京科技大學等 11 位專家學者到此實習研究, 而台灣僅有一位. 建議核能研究所應加強與京都大學原子爐實驗所之合作關係並增加參訪人員.

6. 參考京都大學原子爐實驗所及 HFIR 核子反應器之人力組織, 並配合核能研究所現況與遂行 TRR-II 各年度工作如細部設計,建廠施工,冷熱試運轉乃至未來運轉維修等實際工作需求, 職擬訂核能研究所 TRR-II 反應器廠人力分年進用時間表(附圖四)及未來之組織架構(附圖五),建議所內相關單位予以評估並協助人員進用.

附圖四　TRR-II 人員進用時間表　　2/2/2001, 石志堅

項次	年度	進用人數	進用原因(完成事項)
1.	2001	2	①廠用儀控界面運轉評估及控制室急停、警報信號之篩選訂定 ②實驗設施界面運轉評估及其進入控制室之急停、警報信號之篩選訂定
2.	2002	5	①運轉限制條件(主冷卻水、電力、保護、控制、通風、廠房等系統)訂定 ②運轉規範之訂定 ③配合建造細部設計(91.7~93.6)完成各系統 SDD 運轉評估與細部設計修正
3.	2003	8	①配合工程建造細部設計(91.7~93.6)完成系統運轉程序書、啟爐程序書、測試程序書、維護程序書 ②建立試運轉相關文件之管制作業 ③運轉系統訓練教材之編寫
4.	2004	12	①完成運轉人員系統訓練與考照 ②參與反應器改建各系統安裝與測試工作(2004.7~2005.10) ③完成試運轉團隊之建立 ④完成運轉限制條件與運轉規範之核定 ⑤完成緊急應變計劃 ⑥完成試運轉用儀器機具及重要組件之準備 ⑦完成廠區保全計劃
5.	2005	32	①完成試運轉前之準備工作及運轉團隊之建立 ②維修人員訓練與能力之前置建立 ③參與反應器冷試車(2005.11~2006.7) ④完成核子保防(重水與核燃物料盤存) ⑤完成環境報告 ⑥完成工安消防計劃 ⑦完成輻射防護計劃

			⑧完成品保計劃 ⑨完成首次啟爐臨界中子源及中子量測系統之安裝與測試 ⑩完成燃料裝填申請許可及燃料裝填準備工作
6.	2006 2006.7.1 First critical	16	①繼續參與反應器冷試車及進行反應器熱試車(2006.7~2006.12) ②爐心營運與反應器功率提升試驗 ③系統評估改善 ④燃料整備 ⑤維修人員及能力後續建立 ⑥20MW 反應器運轉執照申請 ⑦庫房料帳管制 ⑧行政支援人力 ⑨文件管制整備
7.	2007 計劃結束		①20MW 反應器運轉執照核發 ②反應器正式運轉服役



附圖五 TRR-II 反應器廠組織表

附錄一　橡樹嶺國家實驗室運轉維修心得

壹.　**HFIR** 原子爐簡介

1. 前言

橡樹嶺國家實驗室(Oak Ridge National Laboratory, ORNL)屬於美國能源部委託田納西大學及貝泰能源公司經營之國家實驗室, 其高中子通量同位素反應器 (High Flux Isotope Reactor , HFIR)為知名之世界最高中子通量($2.3x10^{15}$ n /sec.cm^2)研究用反應器, 位於田納西州橡樹嶺市, 現有員工 200 餘人(含支援人力如保健物理, 實驗設施技術等 60 人),其編制為一個直屬橡樹嶺國家實驗室的獨立研究用反應器組(Research Reactor Division, RRD), 其下包括運轉部門,維護部門,設計部門,計畫與訓練部門及行政支援部門等,每年約有 200 名來自於全國以及國外之研究人員進行各項中子實驗. 該原子爐主要任務為中子散射實驗並生產同位素如 Pu-239, Cf-252 供工業,醫學,及學術界使用.

高中子通量同位素反應器 (HFIR) 由美國 AEC 於 1959 年 3 月責成橡樹嶺國家實驗室設計,1961 年 6 月開始建造, 1965 年 1 月建造完成後進行熱流與機械系統測試, 並於 1965 年 8 月 25 日達到初次臨界, 其最大熱功率為 100 MW, 實驗靶區 (Target Region)最大熱中子通量為 $2.3x10^{15}$ n /sec.cm^2. 初次臨界後, 經逐步提升功率測試 (Power Ascension Test), HFIR 於 1966 年 9 月達額定功率 100MW 運轉.

1986 年 11 月, HFIR 研究人員由 Surveillance Program 測試報告發現, 其爐心壓力槽受中子照射脆化程度比預測更為嚴重, 為維持壓力槽之結構完整性, HFIR 決定停爐兩年半以重新分析評估主冷卻水壓力與壓力槽可承受之熱限, 1989 年 4 月獲美國能源部批准, 重新啟動於 85 MW 運轉迄今.

註: {當年 HFIR 由 1959 年開始設計到 1966 年 9 月額定功率 100MW 運轉共費時約 7.5 年, 與 TRR-II 計畫時程相當; HFIR 建造完成後進行熱流與機械系統冷試車測試共費時約 7 個月,與 TRR-II 計畫運轉小組規畫 6 個月相當.}

2.　HFIR 實驗設施

2.1　實驗導管:

高中子通量同位素反應器(HFIR)共有四條水平中子散射導管(Inner Diameter is 10 cm),分別為:

2.1.1　One Through Tube: HB-1(Spectrometer).

2.1.2　One Through Tube: HB-4 (Wide Angle Neutron Diffractometer WAND). HB-4 並包括 30 meters 小角度散射裝置(Small Angel Neutron Scattering, SANS).

2.1.3　One Radial Beam Tube: HB-2 (Spectrometer)

2.1.4　One Tangential Beam Tube: HB-3 (Spectrometer)

2.2　照射設備

2.2.1　爐心中央水送管 x 1 (Hydraulic Rabbit Tube): 提供爐心高中子通量短期同位素照射.

2.2.2　垂直照射管 : 位於永久鈹反射體內之快中子(> 0.1 Mev)照射管, 可進行輻射損傷研究與中子活化分析研究.

2.2.3 傾斜照射管 x 4 : 位於鈹反射體內, 傾斜角 49 度, 用於較小之中子通量實驗.
2.2.4 氣送管 x 2 : 位於鈹反射體內, 用於中子活化分析研究.
2.2.5 Target Bundle x 30 : 位於 Core Centerline Flux Trap 內, 可生產同位素及進行高中子通量材料研究.
2.2.6 Peripheral target position x 6: 位於 Flux Trap outer edge.
2.2.7 Spent Fuel Irradiation Facility: For gamma irradiation in the reactor pool. The initial (maximum) dose rate in the facility is approximately 1 x 10^8 R/h.

2.3 冷中子源設施(Cold Neutron Source Facility, CNS) --- 建造安裝中

HFIR 冷中子源設施目前已完成緩速腔, 傳送管, 冷凝器, 壓縮機, 氦氣冷凍機等設備之製作,建造與安裝, 其進度已達 70%,預定於下次停爐大修(2001 年)時連接冷中子源導管, 並預定 2002 年運轉. HFIR 冷中子源設施屬於橡樹嶺國家實驗室研究用反應器組, 該冷中子源設施由實驗導管 HB-4 引出, 使用 Supercritical gas 氣態氫做爲緩速腔之冷卻劑,正常運轉溫度爲 20K, 緩速腔內徑 2.5 in.,材質爲鋁合金 Al- 6061-T6. HFIR 冷中子源緩速腔, 傳送管, 冷凝器已做過破壞力學分析及流沖振動分析. 分析報告編號: ORNL/TM-13498 HFIR CNS Reference Design Concept, May,1998.

註: {因爲鋁合金 5000 系列有較多的鎂含量, 焊接性比鋁合金 6000 系列要好; 但對於鎂含量高的鋁合金 5000 系列, 因中子累積通量 (Neutron Fluence) 越多越易造成鎂 Deposition 腫脹變形, 日本京都大學原子爐功率只有 5MW, 緩速腔處最大熱中子通量僅 $1x10^{13}$ n /sec.cm^2, 照射後緩速腔, 傳送管, 冷凝器沒有腫脹變形之顧慮; 但是核能研究所 TRR-II 功率 20MW, 最大熱中子通量高達 $3x10^{14}$ n /sec.cm^2, 緩速腔照射後有腫脹變形之顧慮, 1999 年 5 月經 TRR-II 計畫結構小組完成使用壽命年限評估並呈報計畫決定: TRR-II 冷中子源緩速腔使用鋁合金 6000 系列之 Al 6061-T6.

針對此重要議題之驗證, 職與 HFIR 冷中子源設施負責人 Dr. D. Selby 及 Dr. Bill Hill 討論緩速腔材質使用年限評估及材料選擇之問題時, Dr. Selby 稱因 HFIR 最大熱中子通量高達 $2.3x10^{15}$ n /sec.cm^2, 緩速腔若使用鋁合金 5000 系列則有腫脹變形之顧慮, 所以 HFIR 冷中子源緩速腔, 傳送管, 冷凝器均使用鋁合金 6000 系列.

此結論與 TRR-II 計畫於冷中子源基本設計之初, 結構小組早在 1999 年 5 月即針對鋁合金之輻射特性, 並依照 1980 年 Dr. Farrell 於 ORNL HFIR 對鋁合金 5000 系列 與 1990 年 Dr. John Weeks 於 BNL HFBR 對鋁合金 6000 系列之研究實驗報告, 同時考量 TRR-II 最大熱中子通量特性, 對 TRR-II 冷中子源緩速腔做 Sizing Calculation 評估使用壽命與應力分析後,作成選擇鋁合金 6000 系列爲緩速腔, 傳送管, 冷凝器之材料互相吻合, 從而取得驗證與信心.
至於破壞力學分析及流沖振動分析, TRR-II 冷中子源緩速腔則尚未分析}

3. 運轉方式::

高中子通量同位素反應器(HFIR)原子爐型式爲鈹反射體(Beryllium-reflected), 輕水緩和與輕水冷卻, 使用高濃縮 U-235 燃料之 Flux-trap type 反應器, 運轉週期 28 天(包括運轉 23 天燃料更換及維修 7 天). 爐心組件座落於 8 英尺直徑之壓力槽內, 而壓力槽則位於反應器水池中. 其相關運轉重要參數如下:

3.1 燃料 :

- 1 根燃料, 包括 Two Concentric Fuel Elements. Inner and Outer fuel plates are curved in the shape of an involute.
- 93% U-235 高濃縮 U-Al 合金燃料
- 製造廠: 橡樹嶺國家實驗室
- 燃料外觀呈渦捲滾筒狀, Total fuel length is 31.125 in., Fuel plate is 24 in., Active fuel length is 20 in.
- 燃料 Outer annulus: 369 plates with Aluminum cladding, Inner annulus: 171 plates with Aluminum cladding. A burnable poison (Boron) is included in the inner fuel element to reduce the negative reactivity requirements of the control plates.
- 燃料 Outer diameter is 17.134 in., Middle diameter is 11.250 in., Inner diameter is 10.590 in. Coolant gap is 0.05 in.
- The fuel (U_3O_8-Al) is non-uniformly distributed along the arc of the involute to minimize the radial peak-to-average power density ratio.
- Central Flux Trap Diameter: 5.067 in.
- A typical core loading is 9.4 Kg of U-235 in total which consists of 6.8 Kg U-235 in the outer element and 2.6 Kg U-235 in the inner element and 2.8 gram of B-10 in the inner element.
- The average fuel lifetime with typical experimental loading is approximately 23 days at 85 MW.
- Concentric cylinders for fuel, control elements, and reflector.

- The fuel region is surrounded by a concentric ring of beryllium reflector approximately 1 ft thick which is in turn subdivided into 3 regions: the removable, the semi-permanent, and the permanent reflector. The first two regions can be removed through the quick opening hatch for replacement due to radiation damage. The permanent beryllium reflector is replaced when the need is indicated by periodic inspection and analysis. It is estimated that the permanent beryllium will required replacement after 275,000 ~ 300,000 MWD of operation, or approximately 13 years at the HFIR's power level, the next time is projected for midyear 2000. 註 1: HFIR 永久鈹反射體上次更換時間為 1987 年. 註 2: TRR-II 未採用鈹反射體.

- The beryllium reflector is surrounded by a water reflector of effectively infinite thickness. In the axial direction, the reactor is reflected by water.
- In order for the HFIR fuel elements to become critical, they must be in the presence of a reflector.

- There are approximately 10 spent fuel elements generated in a year since there are about 10 reactor cycles in a year.

- HFIR 用過後燃料運送至美國南卡羅萊納州 Savannah River 實驗室作再處理.
- HFIR 運轉 35 年從未發生燃料破裂事件.
- ORNL ORR(Oak Ridge Research Reactor)反應器為世界上第一個使用 U_3Si_2-Al 燃料之研究用反應器(TRR-II 亦採用此種 U_3Si_2-Al 燃料). 註: {職與 HFIR 資深核燃料專家 Mr. Rodney Knight (已年屆 78 高齡, HFIR 仍不讓他退休, 因為在 HFIR 其核燃料專業無人可以取代)討論 U_3Si_2-Al 燃料, 亦提及 TRR-II 準備與 CERCA 及 B&W 兩家核燃料公司接觸, 並詢問他對 U_3Si_2-Al 燃料之意見, 其稱截至目前為止 U_3Si_2-Al 燃料尚無破裂記錄, 係屬於穩定性高的燃料; 再詢問他那家較好, 則答覆 HFIR 與 CERCA 及 B&W 兩家公司均有合約, 但各有缺點.}

3.2 Fuel Cycle:

A fuel cycle for the HFIR normally consists of full-power operation at 85 MW for a period of from 22 to 23 days (depending on the experiment and radioisotope load in the reactor), following by an end-of-cycle outage for refueling. A typical end-of-cycle refueling outage lasts 5 to 7 days.在 end-of-cycle outage 期間, 實驗樣品棒可抽出或放入; 控制棒亦利用此期間進行校正,保養,及測試. There are 10 cycles in a year for HFIR.
Interruption for a fuel cycle for experiment installation or removal is strongly discouraged. Deviations from the schedule are infrequent and are only caused by periodic change out of major reactor components and its malfunctions.

3.3 控制棒：

- 四塊 Quadrant 66 in.長之粗調 Control Plates 向上抽出以提升功率.
- 一根 66 in.長之微調 Shimming and Regulating Control Cylinder which has no safety function 向下抽出以提升功率.
- 五根控制棒正常升降速度如下
  1). Withdraw: 5.75 in. per minute by shim motor driven by electrical power.
  2). Insertion: 50 in. per minute by air motor
- 每根控制棒依中子吸收特性區分爲黑灰白三段, 黑色段控制棒中子吸收最強, 材質爲 22 in. 33 Volume % Eu_2O_3, 灰色段控制棒中子吸收其次, 材質爲 5 in. 40 Volume % Ta-Al; 白色段控制棒無中子吸收功能,材質爲鋁合金.
- The control plates, in the form of two thin poison-bearing concentric cylinder, are located in an annular region between the outer fuel element and the beryllium reflector. Reactivity is increased by downward motion of the inner cylinder which is used only for shimming and regulation and has no fast safety function.
- The outer control cylinder has 4 separate quadrants, each having an independent drive and safety release mechanism. Reactivity is increased as the outer plates are raised.
- 控制棒驅動機構位於爐底室, 正常運轉時由驅動機構將四塊粗調 Control Plates 向上抽出, 並同時將一根微調 Shimming and Regulating Control Cylinder 向下抽出; 急停時 Magnetic Power 消失, 四塊在上之粗調 Control Plates 靠重力及彈簧力自由落下插入爐心(Time of Flight 共需 450 ms from scram initiation signal to fully seated, including 50ms mechanical delay for control switch). 急停時微調 Shimming and Regulating Control Cylinder 不動作.

- 控制棒在運轉模式 I, II, III 之運轉限制條件 (LCO):
  1). 運轉限制條件 LCO 3.1.3.4: 若控制棒 Magnetic Release Time exceeds 12 millisecond, 反應器不准啓動.
  2). 運轉限制條件 LCO 3.1.1.3: 若控制棒 Time-of-Flight exceeds 450 ms (HFIR 實際測試值爲 300 ms), 反應器不准啓動.

3). 運轉限制條件 LCO 3.1.1.1: Without strongly absorbing experiment in the removable beryllium, the five estimated symmetric critical control elements position shall be greater than or equal to 16.3 in.(a distance from the fully insert seated position) withdrawal prior reactor startup to maintain a enough shutdown margin. 否則反應器不准啓動.

4). 運轉限制條件 LCO 3.1.1.2: The difference between estimated and actual critical position shall be less than 0.5 in. 否則反應器不准啓動.

5). 運轉限制條件 LCO 3.1.2: Adequate shutdown margin shall be verified by demonstrating the core is sub-critical in the water-immersed and water-reflected condition and meeting 運轉限制條件 LCO 3.1.1.1 by a core reactivity measurement performed in a critical experimental facility or a core reactivity verification performed in the HFIR by source multiplication.

6). 運轉限制條件 LCO 3.1.3.1: The combined maximum rate of reactivity addition by the shim motors for all 5 control elements and by the servo system regulating motors shall be limited to $ 0.91/sec(0.00692 delta K/K per second). 否則反應器不准啓動.

7). 運轉限制條件 LCO 3.1.3.2: The manual switch shall be "Operable" for mode 1 and 2. 否則反應器不准啓動.

- 反應器必須處於次臨界之四種控制棒狀態:

1). All control elements fully inserted (i.e.燃料更換期間)

2). Four control elements inserted, any one control element fully withdrawn

3). 3-out-of-4 scram from critical, the shim-regulating cylinder immobilized

4). 3-out-of-4 scram from critical, one shim safety plate fully withdrawn, the shim-regulating cylinder immobilized.

- 正常運轉僅微調 Regulating Control Cylinder 為 PID Servo Control depends on the difference between linear power and power setting demand to insert into or withdraw from the core.
- 控制棒驅動機構之設計,可選擇五根同時上下,亦可選擇單(數)根同時上下. 急停時任何單根控制棒落下即可將反應器安全停爐.
- All control plates have three axial regions of different poison content designed to minimize the axial peak-to-average power density ratio throughout the core lifetime. 註: {建議 TRR-II 控制棒設計考量此重點}
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3.4 HFIR 中子量測儀器:

3.4.1. Wide range fission chambers counting system x 3:

There are three wide range fission chambers are used for control of the reactor start-up to develop neutron flux signals detected from fission chambers. Fission chambers are driven by electrical servo motors through a gearbox. Automatic positioning of the fission chambers through a functional generator enables the system to provide reactor power and period signals from source range to maximum power, a range of approximately 10 decades. (參考圖-24 HFIR System Overview).

3.4.2. CIC x 3 (斜插入壓力槽, 為 Fixed position and can be adjusted mechanically, they are horizontally located on each side outside the core for medium and high power range). One is for Lin- N and the other is for Log- N.

- 3.4.3. The set point for each fission chamber is 10,000 cps in order to keep fission chamber from getting damaged due to over neutron exposure when reactor power increase. There is a servo motor for each FC at the bottom of reactor pressure vessel to allow FC withdraw downward automatically from the core when reactor power is above 10% of full power. So, there are fission chamber position indicators for their position inside core. 註: {TRR-II 中子量測儀器之 5 個 Fission Chambers(3 for RPS and 2 foe RPCS)設計, 是否已考量此重點?}

3.5 停機餘裕 Shutdown Margin:

Adequate shutdown margin shall be verified by demonstrating the core is sub-critical in the water-immersed and water-reflected condition and meeting 運轉限制條件 (Limit Condition for Operation, LCO)3.1.1.1.

運轉限制條件 LCO 3.1.1.1: Without strongly absorbing experiment in the removable beryllium, the five estimated symmetric critical control elements position shall be greater than or equal to 16.3 in. withdrawal prior reactor startup.

3.4 不同運轉模式下之 HFIR safety limit:

在不同運轉模式下, There are following safety limits for HFIR:

- Flux-to-Flow Ratio: 1.36 at 16,000 gpm, 2.4 at 1500gpm at operating mode 1. 註: {TRR-II primary coolant 爲 constant flow,沒有 Allowable Power vs Flow map to keep TRR-II in the safe operating range 之問題}
- Primary coolant vessel inlet pressure shall be greater than or equal to 318 psig at operating mode 1.
- Neutron power shall be less than or equal to 4 MW in operation mode 2
- Neutron power shall be less than or equal to 175 KW in operation mode 3
- Reactor vessel pressure/temperature shall be on or below the safety limit curve for operating mode 1.
- Primary coolant minimum flow rate > 1350 gpm for mode 1& 2
- Primary coolant minimum flow rate > 850 gpm for a minimum of 12 hours after shutdown from mode 1& 2.
- Primary coolant inlet temperature < 140 F for mode 1& 2
- Seismic acceleration < 0.15 g for mode 1, 2,3 and pool work sub-mode.
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貳. 原子爐運轉詳述

1. 運轉模式:

1.1 功率運轉模式:

乙、.1 Mode 1 – Start (高功率運轉模式):

- It is automatically controlled to 8.5 MW (N_L – 10% of full power range). In this mode, the reactor is started under control of wide range counting system with full primary flow and pressure established.
- When reactor reaches N_L, the servo system takes control of reactor power and the conditions are established for power ascension.
- In start-up, certain safety action set point values are lowered for protection in this low power mode.

1.1.2 Mode 1 – Run (高功率運轉模式):

- Mode 1 Run is defined as servo controlled from N_L to N_F (Full power – 85 MW).
- In this mode the safety action set points are increased to their normal full power settings.

1.1.3 Mode 2 (低功率運轉模式):

- Mode 2 is a low power operation mode with a maximum power of 2.5 MW.
- In mode 2, only 10% of full primary flow is required. Start and Run conditions are defined the same as for mode 1 with N_L = 250 KW and N_F = 2.5 MW.
- In start-up, certain safety action set point values are lowered for protection in this low power mode.

1.1.4 Mode 3 (微功率運轉模式):

- Mode 3 is defined as an operator controlled start-up and operation with a maximum power level of 100 KW with no flow or pressure required.
- All control plates withdrawals are manual.
- In start-up, certain safety action set point values are lowered for protection in this low power mode.

Normal operation for HFIR is Mode 1 full power operation. Normal start-up consists of a mode 3 start-up using a pull and wait approach to critical for verification of new fuel reactivity worth.

1.2 Shutdown Mode:

- The reactor is fueled.
- The control cylinder and/or four plates are fully inserted (i.e., in seat).
- The control switch is in "Operate" position or
- Forced cooling is required per LCO 3.5.1.1

1.3 Secured Mode:

- The reactor is de-fueled or
- The control switch is in the "OFF" position
- Forced cooling is not required per LCO 3.5.1.1

1.4 Pool Work Sub-mode:

Note: The pool work sub-mode may exist concurrent with any operational mode.

- Irradiated target handling activities are occurring.
- Irradiated fuel movements are occurring.
- Hoisting and rigging activities over the spent fuel pools are occurring.

各種運轉模式之間有 key 可以相互轉換,而且與反應器運轉 key switch 相互連鎖, 反應器必須在停爐狀態才可改變運轉模式.

2 保護系統急停方式:

- 不同於核能電廠需要兩路急停信號來自於同一參數使之跳機, HFIR 之保護系統急停特徵爲在 Mode 1 Run 運轉模式下, 下列任何一個急停信號即可使反應器急停:

a). High primary coolant inlet temperature – 130 F.
b). High reactor heat power – 120% of selected mode range.
c) High rate of flux increase – 20%/sec.
d) High % neutron flux level to % primary flow ratio – 1.25.
e) Low primary flow – 1900 gpm.
f) Low primary pressure – 368 psig.
g) High primary gamma radiation activity at vessel outlet – 150% of normal mode 1 background.

3. 功率控制方式:

HFIR has the following power control methods:

- Servo Control System :
  The servo system provides automatic control of power at levels > N_L in Mode 1 and 2.
- Wide range counting system:

The wide range counting system is used for control of the reactor start-up to develop neutron flux signals detected from fission chambers. The fission chambers are driven by electrical motors. Automatic positioning of the chambers enables the system to provide reactor power and period signals from source range to maximum power, a range of approximately 10 decades.

- HFIR 有三種異於急停之功率控制方式分別爲 Setback, Reverse, and Fast reverse which are normally initiated at setpoints lower than the scram setpoints to control transients before the safety system is challenged.

1). A setback is defined as an automatic reduction in reactor power demand in servo system by inserting the inner control cylinder.

2). A reverse is an automatic insertion of all control plates with the normal speed shim motor.

3). A fast reverse is an automatic insertion of the four outer control plates by a unidirectional air motor at a rate of 50 in/min. One example is % flux/& flow > 1.1

- 此外 HFIR 還有一套緊急毒物注入系統 (Emergency Poison Injection System):

A poison injection system using gadolinium is provided as an emergency backup for the normal reactor safety system. The system is only used in an extreme emergency when shutdown cannot be accomplished by using any of the three following methods: Reverse, Air motor insert, and Scram.

4. 啓爐前檢查測試與啓爐程序：

啓爐前檢查, 測試由值班工程師主持, 下達命令給控制室反應器運轉員執行, 運轉經理(課長)在旁監督, 並於各項測試完成後當場簽字核准, 以利進行下一項測試. 測試內容包括:

4.1. Pre-startup check and test for Mode 3 (<100 kw 微功率運轉模式): 3 hours

- Mode switch: Mode 3 position.
- Reactor switch: Operate position.
- Performing five control rods up/down and drop flight of time test.
- Performing scram test for Channel A, B, C of the protection system for all reactor scram signals.
- 控制棒預估臨界位置 Estimated Critical Position (ECP) test:

1). Reactor operator announces: “ Reactor will be startup in mode 3”

2). Rising 3 fission chambers to 2.7 in. position

3). Checking primary coolant pressure is 475 psig

4). Withdraw five control rods at the same time until they reach 10 in. position.此時記錄 Channel A,B,C 之中子 Counting rate, channel 1: 271; channel 2: 646; channel 3: 300.同時有爐心物理師於控制室以電腦計算出控制棒預估臨界位置.

5). Withdraw five control rods at the same time until they reach 12 in., 15in., 17 in., 18 in. position, respectively. And also record Channel A,B,C neutron Counting rate M.

6). When the reciprocal of neutron counting rate 1/M approach to zero for position 18 in.(M = 0.08), that means it is the almost critical position for the control rods. 此時爐心物理師亦於控制室以電腦計算出控制棒預估臨界位置爲 18.55 in.

7). 此控制棒預估臨界位置 18.55 in 即爲值班工程師於 Mode 1 高功率運轉模式下運轉之臨界位置參考.

8). Reactor operator announces: “ Reactor will be shutdown in mode 3”, select scram switch and then five control rods drop freely, the reactor is in the S/D status again.

4.2. Pre-startup check and test for Mode 1 (高功率運轉模式)

- Mode switch: Mode 1 position.

- Reactor switch: Operate position.
- Performing scram test for Channel A, B, C of the protection system for all reactor scram signals.
- Current ramp test.(以下七項測試與控制棒位置無關, 五根控制棒均在最低 Seated 位置)
- Heat power test.
- Depressurization test.
- Primary inlet temperature test.
- Rate test.
- Low flow test.
- Flux flow test.

4.3 啓爐程序:

做完 4.2. Pre-startup check and test for Mode 1 後, 反應器即可啓動, 步驟如下:

4.3.1 Put reactor power demand switch in 10% (8.5 MW).

4.3.2. 控制室以 P/A system 廣播, 反應器即將於高功率 Mode 1 啓動.

4.3.3 Put three fission chambers in the same position as mode 3.

4.3.4 同時抽出五根控制棒至 Mode 3 已算出之控制棒預估臨界位置 18.55 in. 此時反應器功率自動上升至 8.5MW.

4.3.5 以 P/A system 廣播, 反應器已於 8.5MW 功率運轉.

4.3.6 檢查 Neutron counting rate, Log rate, Linear rate, reactor period 均正常.

4.3.7 將控制方式由手動改爲 Servo Control 自動方式運轉

4.3.8 此時由值班工程師下達命令給控制室反應器運轉員提升 Reactor power to 100% in 20% power increment, 控制室反應器運轉員於每個 20% power increment 達到後均需以 P/A system 廣播, 直到全功率 85MW 運轉爲止.

4.3.9 以上各步驟從 10% Power (8.5 MW) 到全功率 85MW 運轉, 只需 5 分鐘, 僅靠轉動唯一的 Reactor power demand setting switch 即可達到提升功率之目的. 5 Control rods and 3 fission chamber position are kept unchanged.

4.3.10 控制方式由手動改爲 Servo Control 自動方式運轉後,第五根控制棒會因燃料棒燃耗而自動抽出爐心調節位置, 以補償因燃料棒燃耗而損失之反應度.

以上各步驟從 10% Power (8.5 MW) 到全功率 85MW 運轉, 唯一要注意的是 Reactor 每提升 20MW 功率前,必須先開大次冷卻水閥 FCV 以防止主冷卻水溫度超過 120F 造成 Pressure Vessel Embrittlement}.

反應器於高功率 Mode 1 啓動過程中需注意下列事項:

1). Normal operation for HFIR is Mode 1 at full power operation. Normal start-up consists of a mode 3 start-up using a pull and wait approach to critical for verification of new fuel reactivity worth.

2). After verifying the fuel, the reactor is then started up in Mode 1 Start to N_L (10% full power, 8.5 MW). At N_L, the reactor comes under the control of the servo system and is allowed to stabilize. Then switching to the “Run” condition.

3). When the reactor power is above 10% of full power, operator may withdraw 3 fission chambers from core region in order to keep neutron counting rate under 50,000 cps, otherwise the fission chamber will be damaged due to neutron overdose. Normally we keep the indication of F.C around 20,000 cps.

4). HFIR 反應器正常在高功率運轉模式下運轉於 85MW, 平均燃料周期依爐心實驗負載而不同, 約 21 ~ 26 天.

5. 停爐程序**:**

可選擇手動停爐或以電腦指令急停反應器(欲測試控制棒降落時間 Flight of Time).

反應器停爐後, 要依停爐程序書之步驟做停爐檢查, 首先將第五根控制棒由爐心抽出確保反應器安全, 其次將控制棒驅動機構磁鐵電源鎖匙, 反應器 Operate/Off 轉換鎖匙, 控制電源鎖匙, 保護系統控制面盤鎖匙拔出, 並將運轉模式鎖匙置於 Shutdown Mode 位置後拔出, 關閉 Recorder, Chart, Start up Monitor 電源, 3 Fission chamber 手動下降到底, 停止主冷卻水 AC Pump,次冷卻水 Pump 及八台冷卻水塔風扇運轉後即完成所有停爐程序.

停爐後僅維持下列設備運轉:

- Pony pumps for decay heat removal
  - Spent fuel clean up pump
  - Primary clean up pump
  - Sweep gas blower
  - Cooling tower pump
- Compressor air system

6. 廠區巡視抄表**(Building Check):** 1 time per shift, 2 times per day, 9 AM and 20 PM.

7. 中子量測方式**:**

7.1 Wide range fission chambers x 3:

There are three wide range fission chambers are used for control of the reactor start-up to develop neutron flux signals detected from fission chambers. Fission chambers are driven by electrical servo motors through a gearbox. Automatic positioning of the fission chambers through a functional generator enables the system to provide reactor power and period signals from source range to maximum power.

7.2. Compensation Ion Chamber x 3: One is for Lin- N and the other is for Log-N.

7.3. The set point for each fission chamber is 10,000 cps in order to keep fission chamber from getting damaged due to over neutron exposure when reactor power increase. There is a servo motor for each FC at the bottom of reactor pressure vessel to allow FC withdraw downward automatically from the core when reactor power is above 10% of full power. So, there are fission chamber position indicators for their position inside core.

8. HFIR Scram Reduction Program:

8.1 HFIR PRA Program:

HFIR had performed PRA for more than 20 years, discussing with HFIR Dr. Mark Linn about the reactor scram reduction program, he suggests TRR-II had better conduct PRA as early as possible since PRA is a management tool more than a technical tool, there are many benefits from PRA as described below:

- Under limited budget condition and to use money more efficiently, PRA can help and improve the reactor operation and system safety.

- PRA can tell us where are the weakest points in our plant, what significant enhancements should be done first in the plant system.
- Good PRA program can reduce the amount of reactor scrams, now DOE is very satisfied with HFIR for their less than one unplanned scram per year, this is the contribution of PRA analysis results.
- The results of PRA program can provide the important and essential inputs of significant scenarios consequences for the analysis of reactor emergency planning zone.

8.2 Scram Reduction Program in HFIR:

- Started from 1992, HFIR changed their safety channels test program, they tested safety channels during the HFIR outage period instead of on-line power operation as they used to do. So, HFIR dropped the scram frequency from 5 ~ 6 unplanned scrams per year before 1992 to less than once unplanned scrams per year after 1992.
- HFIR has a set of risk management program to reduce their human errors contributed to reactor scram.
- HFIR had performed its PRA program to improve and enhance the function of safety system, so to reduce the reactor scram frequency.

9. HFIR QA Plan:

The QA plan for the HFIR is based on ASME/ANSI NQA-1.

10. 廠房系統:

The primary coolant enters the pressure vessel through two 16 in. diameter pipe above the core, and exits through an 18 in. diameter pipe beneath the core. The flow rate is 16,000 gpm (1.01m^3/s), of which 13,000 gpm (0.82m^3/s) flows downward through the fuel region. The reminder flows through the target, reflector, and control regions. Reactor core coolant flow is 0.82 m^3/sec.

The primary coolant inlet pressure is 468 psig (3.33 MPa), inlet coolant temperature is 120F (49C). Reactor Start up 提升功率前,必須先開大次冷卻水閥 FCV 以防止主冷卻水溫度超過 120F 造成 Pressure Embrittlement.

The exit temperature is 156F (69C), the pressure drop through the core is about 110 psi (7.58 MPa).

10.1 The primary coolant system includes the following:

1). Primary AC Pump x 4:

- Three of them are driven by 2200V offsite power with the fourth maintained in standby.
- Single stage, vertical, centrifugal pumps directly coupled to 600 HP squirrel cage induction motor.
- Normal flow rate is about 1.01m^3/s and pressure is 3.33 Mpa.

2). DC pony motor x 3:

- In the normal operation, 3 HP pony motors are driven by DC power converted from an inverter, while during loss of offsite power (LOOP), pony motors are driven by two physically separate trains of DC battery.
- The 1300 gpm flow rate pony motor has to run above 12 hours to remove the decay heat after LOOP.
- Pony motors are on the back of primary AC motor just like a pony is on his mother’s back. Pony motors and the primary AC motors share a common shaft and impeller to pump primary water.

- Safety analysis has shown that 1000 gpm is adequate to protect the core from damage following a scram from full power.

3). Emergency Depressurization System (EDS):

The EDS functions to protect the reactor vessel from brittle fracture in the event of a low temperature/high pressure situation. If core inlet temperature drops below 90 F at pressures greater than 225 psig, the EDS trips the pressurizer pumps and opens two valves which relieve primary pressure to the letdown header.

4). 運轉限制條件

- 運轉限制條件 LCO 3.5.1.1 Decay heat removal system:

LCO A: After shutdown from operation at mode 1 or mode 2, at least one pony motor pump shall be in operating, pumping at least 1000 gpm for a minimum of 12 hours.

LCO B: At least one pony motor battery bank associated with a pony motor meeting LCO A shall be “Operable”.

- 運轉限制條件 LCO 3.5.1.2 Pony motor pump/Battery banks:

LCO A: At least two operable pony motor pumps shall be in service

LCO B: At least 2 operable pony motor battery banks connected to the pony motor pumps in criterion A shall be in service and shall be separated by an operable fire barrier with a 1.5 hours fire rating.

- 運轉限制條件 LCO 3.4.1 Primary coolant PH:

  LCO : The PH of the primary coolant shall be within the following range:

  4.8 < PH < 5.2 for mode 1

  4.8 < PH < 6.0 for mode 2

  The PH may be outside the specified range by up to 0.1 for a total of 8 hours operating time. For a period greater than 8 hours, the reactor have to go to the shutdown mode to wait for a technical evaluation.

10.2 The secondary coolant system has:

1). Secondary Pump x3:
- 2/3 operation, all driven by 2200 V offsite power.
- Normal flow rate is 26,000 gpm.

2). Cooling Tower Fan x 8 (two speed).
- Cooling tower is a four cell to transfer 111 MW of heat to the atmosphere.
- About 600 gpm of water is supplied to the tower from the portable system to make up the losses due to evaporation, drift, and tower blow-down. The cooling tower basin is 400,000 Gallon.

10.3 HFIR emergency power system is described as following:

1). Emergency Power System:
- Normally, Two 13.8 KV feeders supply to HFIR, one is preferred feeder with the other acting as alternate. It takes 2 seconds for an automatic transfer upon loss of incoming voltage.
- In the event of LOOP, the emergency system automatically starts two D/G. For reliability, the critical loads are split between the diesel generators and the diesels have different types of starting systems.以下爲不同之啓動方式:

- No 1 diesel is an electric start diesel supplied with its own battery and charger. No 2 diesel is air start and has its own air receiver and compressor. 註: {此爲避免 Common mode failure 而設計, TRR-II 緊急柴油機是否有考量此點?}
- Major loads on the Emergency power system include the pony motor battery charger, confinement exhaust fans, and the instrument power system.

2). 輔助緊急柴油機 (Auxiliary Emergency Power Generators, AEPG's):

- Two AEPG's are provided for the sole purpose of serving as a third level backup power supply for the pony motor battery chargers. When LOOP, each pony motor battery is sized to supply at least 1000 gpm for 6 hours without being recharged. During this time, one of the AEPG's would be brought to the HFIR and connected to the battery chargers to provide long term decay heat removal. 註: {此點係 HFIR 爲維持電瓶組基本容量,從而降低電瓶組正常運轉維修負荷而設計; 當廠外電源喪失時, 又可適時啓動該輔助緊急柴油機以增加緊急直流電力供應; 與核四廠之 Swing Diesel Generator 設計相當. TRR-II 緊急電源系統沒有此項設計.}
- The AEPG's are stored at the HFIR 7000 area to maintain a separation greater than the path of a tornado.

3). Instrument power:

The instrument power system includes battery chargers and batteries which supply loads critical to the monitoring of the reactor system following a scram due to a power outage.

10.4. HFIR Confinement and HVAC System is described as the following:

- HFIR 反應器廠房採深度防禦縱深觀念, 有四道防線. The first level of confinement is the fuel cladding, primary coolant is the second, the third level of confinement is the ventilation system to maintain a pressure gradient and provide a positive in leakage of air into the areas of highest potential for contamination.
- The reactor building is divided into four zones as following:

1). Zone 1 is clean area such as the control room which is maintained at a slightly positive pressure by separate ventilation fans and dampers. 註: {TRR-II 主控制室亦爲此種設計.}

2). Zone 2 areas are generally clean areas with the potential for contamination. Zone 2 areas are kept at – 0.1 in. water by exhaust fans and regulating the fresh air intakes.

3). Zone 3 areas include all the areas in the main reactor building except for the heat exchange cells and the pipe tunnel. Zone 3 area is kept at –0.3 in. water by exhausting directly to the ventilation system. Zone 3 include the reactor bay, beam room, and experiment room.

4). Zone 4 is the area with the potential of highest activity and is kept at a – 0.4 in. water negative pressure. Zone 4 only includes the heat exchanger cells and the pipe tunnel.

- The exhaust is monitored for beta/gamma activity on the exhaust duct just prior to entering the stack. The exhaust is also monitored at the 50 foot level of the stack for noble gas activity, iodine activity, and particulate alpha/beta activity.
- The filter trains consist of a series of absolute and charcoal filter designed to be 99.97% effective for removing particulate matter > 0.3 microns and to remove > 99% of elemental iodine.

- There are several inhale dampers in HFIR confinement with the similar function as vacuum breaker in TRR. These dampers are gravity dampers and will open automatically to let fresh air enter when the confinement vacuum is too high.
- There is no smoke removal system in HVAC of HFIR.

HFIR Plant Water Supply is from two 1.5 million gallon water storage tank supplied by Y-12 (橡樹嶺國家實驗室核子武器工廠) plant reservoir.

10.5 Instrument Air:
HFIR instrument air system is supplied by one of three main compressors at a nominal pressure of 90 psig to supply pneumatic control valve and instrumentation in the plant.

10.6 Acid and Caustic Systems:
- The nitric acid is diluted to 5% concentration for use in primary PH control.
- Sulfuric acid is stored and used only for PH control for the secondary water system.

10.7 HFIR Plant Communication System:
- Walkie-talkie
- Intercom system
- Normal phone
- P/A system

11. Earthquake Design Requirement:
- Design earthquake is 0.15 g horizontal ground motion acceleration, scram earthquake is 0.08 g (1g = 980Gal).
- Recent HFIR PRA analysis concluded that only a small fraction of the overall core damage frequency is attributable to seismic-induced failures.
- There is no fault around ORNL HFIR and the seismic activity is very small around HFIR.

註: { Kobe 神戶 earthquake: 0.2 g ~0.25 g (200-250Gal), 1/17/1995, 5:47AM.}
-

12. 主控制室 (Main Control Room, MCR):
有一個主控制室模擬設施(Mock up)供運轉員訓練及緊急計畫演習使用.
主控制室內有下列控制盤面:
1). 計 3 台 Identical but Independent Panel to digitally display and alarm all essential signals.
2). Control and indication for primary pumps/valves, secondary pumps/valves, cooling tower fans, primary and spent fuel cleanup system pump, pressurizer, electrical system, compressor air system.
- All pump switches in MCR has plastic cover for the “stop” switch to avoid false push the button during power operation.
- All process control and flow chart display are in the control console, there is no large display panel in the control room.

3). Three operation modes: Shutdown, Secured and power operation.
4). “OPERATE” or “OFF” control mode transfer key.
5). Control shim rod and Regulating rod control switch and indication.

6). Control rods position indication.
7). Power demand setting switch: 100kw, 1Mw,. 85Mw.
8). HP area indication and monitors:

- Reactor bay
- Experiment room
- Beam room
- Pool side
- Sub-pile(爐底室)
- Third level

9). Auto shim servo control system.
10). Control power, magnetic power and recorder power.
11). All protection system scram signal.
12). Linear, Log Counting Rate (LCRx2), period indication.
13). Alarm signal is described on the display panel, operator can see and acknowledge the alarm.
14). Microphone: Push button default public address system.
15). Emergency push button (plastic cover).
16). Scram reset, Reset, Acknowledge.
19). Protection system relay and connector.
20). All important pool and tank level such as reactor pool, spent fuel pool, sub-pool, critical pool, etc.
21). There is no door key for the control room in HFIR.

13. 爐體:

- With a cover shield hatch which is operated manually by a special design handle on the top of reactor core.
- Without decay tank, without thermal layer.
- There is a smart reactor pool leakage detecting system in HFIR which consisting of 11 tubes, one end of each tube is connected to tank leakage detecting point while the other end is connected to a plastic transparent bottle, operator can realize the leakage condition by checking the level of the bottle.
  註: { HFIR reactor pool leakage detecting system 可供 TRR-II 參考.}
- HFIR core components material is Al-6061,
- 反應器爐心組件座落於 8 英尺直徑, 26 英吋高之壓力槽內, 而壓力槽則位於反應器水池中. 壓力槽頂端蓋板爲 14 英吋厚之碳鋼 cladding on both side with stainless steel, 低於池面 17 英尺. 壓力槽材質爲碳鋼 cladding on both side with stainless steel.
- There is a quick open hatch attached to 壓力槽頂端蓋板, 以利燃料更換.
- The reactor vessel is sealed on the bottom by a 40-inch diameter bottom head.
- 爐底室高約 2 米,不具 Water Tight 防洩功能.

14. HFIR 首次臨界啓爐程序:

In 1965, HFIR used 3 permanent fission chambers for reactor operation to detect the neutrons from Antimony Sb-124 neutron source which were put inside the HFIR beryllium reflector. Three fission chambers were located under the bottom of the reactor vessel about 10 ~ 12 inches away. By means of (r , n) reaction of Sb-124 with Be inside the reflector, the first criticality was achieved in HFIR.

註: {Discussing with HFIR Dr. Dick Rothrock in this regard for TRR-II project, he suggests TRR-II may use Cf-252 or (Am + Be) as the first start up neutron source since there is no beryllium in TRR-II, the strength of start up neutron source has to be greater than 10^6 neutrons/sec, and to put the neutron source as close as possible to the core center. He also suggests that TRR-II had better borrow two high sensitivity (counting rate > 10 ~ 50 neutrons/sec) fission chambers from the local university, put these two high sensitivity fission chambers close to the core. In this case, TRR-II has two benefits, one is we don't need so strong neutron source to start up the reactor, the other is we don't need to use thicker-shielding cask to keep the neutron source.

KUR Mr. Ishihara suggests: The BF_3 is not stable due to their strong gamma ray ionization, but BF_3 sensitivity is 10 times better than Fission Chamber. So in the first criticality, KUR used BF_3 as well as fission chamber as the neutron detector.}

15. HFIR 長期停爐後啓爐程序:

1986 年 11 月, HFIR 研究人員由 Vessel Surveillance Program 測試報告發現, 其爐心壓力槽受中子照射脆化程度比預測更爲嚴重, 爲維持壓力槽之結構完整性, HFIR 決定停爐兩年半以重新分析,評估主冷卻水壓力與壓力槽可承受之熱限, 1989 年 4 月獲美國能源部批准, 重新啓動於 85 MW 運轉迄今.

與 HFIR Dr. Rothrock 討論, HFIR 停爐兩年半後於 1989 年 4 月重新啓動, 其 Start up 方式與 HFIR 首次臨界啓爐程序不同, 因爲 Sb-124 之半衰期僅 60 天, 當年之中子源 Sb-124 已不能使用.

1989 年 HFIR used Curium-96, it is a spontaneous neutron source, to start up the reactor. HFIR put Curium-96 in the flux trap in the center core region, and also used their current three fission chambers to detect the neutrons for the reactor criticality.

註: {Dr. Rothrock suggests there are two important points we have to keep in mind for the neutron detecting system:

1). To decide how many neutrons we need to detect, this is related to the location and the sensitivity of fission chamber,

2). To decide how many Curie for the strength of neutron source.

KUR had shutdown for almost a whole month in August 2000, so, after shutdown for a month, KUR operator use Am+Be neutron source which was stored temporarily in the core tank storage rack to re-start up their reactor, and the neutron detecting system is still the same previous 2 fission chambers.

For current KUR, since there is a lot of dirty gamma emitter material inside the core, BF_3 counter will be affected by gamma ray, so KUR doesn't use BF_3 counter any more for their re-start up after long term shutdown.}

16. HFIR 輻射防護:

HFIR 反應器大廳, 地下室之 Water ring room 包括 primary coolant sampling room, process water system room, primary head tank room, HVAC and chiller room, ion-exchanger room 等房間之走道均爲清潔白區, 不必換套鞋, 部分黃區地面僅以油漆畫線以利運轉操作及維修工作.

17. 備用停機面盤(Alternative Shutdown Panel):

There is no 備用停機面盤, only some emergency scram push buttons are in the HFIR different site for emergency use.

18. Tritium concentration limit in HFIR:

Since HFIR fuel element is 93% U-235 高濃縮 U-Al 合金燃料, so there is no heavy water system in the HFIR. There is no Tritium concentration limit problem in the HFIR.

19. 廠區安全 **CCTV:**

- 爐頂
- Core

20. 運轉訓練編組人力**:**

20.1 HFIR 運轉人力:

- 5 shifts in total, 12 hours per shift. 7 a.m. to 7 p.m. for day shift and 7 p.m. to 7 a.m. for night shift.
- 5 persons per shift. (1 shift supervisor, 1 technical advisor, 3 reactor operators)
- 2 reactor operators are in the control room per shift (Required by regulation).The other one is conducting the building check.
- 1 health physics personnel per shift support to operation.
- When reactor start up, there are 4 persons in the control room, shift supervisor gives order to two reactor operators, operation department manager supervises all the activities in the control room and counter-signs some start-up check lists document. .
- 1 operation department manager and several system engineers responsible for the system improvement and design change.
- There are 50 people in HFIR operation department (including fuel handling people).

20.2 HFIR 運轉員訓練:

HFIR 有訓練部門, 專司運轉,維修訓練事宜.

- 運轉員 (Reactor Operator, R.O): 一般訓練一年, 若運轉員具海軍艦艇經驗則訓練六個月. 訓練內容包括:

  1).八星期課堂訓練(基本訓練),課堂訓練內容如下:

  · Nuclear physics
  · Heat transfer/Fluid flow
  · Chemistry/Thermodynamics
  · Radiation protection
  · I/C system
  · Experimental facility
  · Security procedure
  · Shift administration

  Then taking the written and system test.

  2).四個月值班在職訓練, 訓練內容如下:

  · On-Job-Train checklist training
  · System checkout training
  · Emergency procedure training
  · Integral plant training
  · Control room mock up training
  · Scenario training

  3). 筆試評估 (Written examination evaluation)

  4). 口試評估與現場操作 (Oral walk-through evaluation)

  5). 運轉經理(課長)現場操作評估 (Operation manager walk-through evaluation).

通過上述訓練考試後由訓練部門經理報請橡樹嶺國家實驗室核發 HFIR 反應器運轉員執照.

- 高級運轉員(Senior Reactor Operator, S.R.O): 一般訓練一年半, 若具海軍艦艇經驗則訓練一年. 訓練內容除包括所有運轉員訓練項目外, 另包括:
  1). Technical Specification Requirement (TSR)
  2). Safety Analysis Report (SAR)
  3). Design Basis Report (DBR)
  4). Plant administration.

  HFIR 建議運轉員訓練必須於 Low power test 前完成, 職則答覆 TRR-II 運轉員訓練必須提前於 TRR-II 冷試車前完成初步訓練, 以利 TRR-II 冷,熱試車.

21. 試運轉及熱試車項目:

1. Primary cooling system performance test.
2. Secondary cooling system performance test.
3. Reactor power calibration 核出力測定試驗
4. Thermal neutron flux distribution (Fission rate mapping)
5. Measurement of temperature coefficient of reactivity effect.
6. Temperature coefficient measurement by local heating.
7. Temperature distribution on fuel plate surface.
8. Heat transmission rate of heat exchanger.
9. Measurement of neutron flux and gamma dose of experimental facilities.
10. Shutdown margin measurement by using HFIRCE-4 experimental code.
11. Control Rod Drive Mechanism test (Magnet Release Time, Time of Flight, etc)
12. Xenon poison effect measurement.
13. Control rod reactivity calibration

22. 實驗設施與控制室界面

22.1 進入控制室之實驗設施急停信號目前沒有, 預留如下:

- Cold Neutron Source Abnormal,
  未來冷中子源實驗設施共有三個急停信號進入控制室反應器保護系統, 以 2/3 control logic 分別急停反應器. 三個冷中子源實驗設施急停信號如下:

1). Hydrogen gas temperature high (200K), normal operating temperature is 20 K.
2). Low pressure of hydrogen gas (7 bar, 1 psia = 14.7 lb/in^2 = 0 psig = 1 bar),
3) Pressure difference between hydrogen gas circulator (0.2~0.3 bar), normal operating delta P is 1 bar.

22.2 進入控制室之實驗設施警報信號如下:

- Hydraulic Rabbit Abnormal

23. HFIR Operation Procedure:

HFIR 運轉程序書非常齊備,共有八冊分述如下:

1. Administration and operation rules and responsibility
2. Pool handling procedure
3. Reactor startup and system components procedure
4. Reactor shutdown and system components procedure

5. Special operation procedure (Shipping cask, transportation, etc)
6. Announciation response(AP), Abnormal operation procedure(AOP), and Emergency operation procedure(EOP)
7. Waste handling procedure
8. Surveillance Test Procedure(STP)

另有緊急運轉程序書包括:

- Emergency response procedure
- Barrel analysis
- HFIR Evacuation Procedure

參. HFIR 原子爐維修:

3.1 HFIR 安全設備維修依據與準則:

- 遵照 HFIR 安全分析報告(Safety Analysis Report, SAR)撰寫 HFIR 技術規範 (Technical Specification Requirement, TSR).
- 遵照 HFIR 安全分析報告撰寫 HFIR 安全設備清單(Safety Related Equipment List, SREL).
- 遵照美國能源部核子設施維修政策 DOE 4330.4B Chapter 11, HFIR 技術規範及 HFIR 安全設備清單, 撰寫 HFIR 安全設備維修計畫書(Maintenance Management Program)
- 最後依 HFIR 安全設備維修計畫書, 撰寫 HFIR 安全設備維修程序書及 HFIR 安全設備測試程序書

3.2 HFIR 安全設備維修計畫書

安全設備維修計畫書內應包括下列文件與內容:

- Maintenance Organization and Administration
- Training and Qualification Program of Maintenance Personnel.
- Maintenance Faculties, Equipment, and Tools
- Types of Maintenance
- Maintenance Procedure Approval and Review
- Planning, Scheduling, and Coordination of Maintenance
- Control of Maintenance Activities, Preventive and Predictive Maintenance
- Post-Maintenance Testing
- Procurement of Parts, Material, and Services
- Material Receipt, Inspection, Handling, Storage, Retrieval, and Issuance
- Control and Calibration of Measuring and Test Equipment
- Maintenance Tools and Equipment Control
- Faculty Condition Inspection
- Management Involvement
- Maintenance History
- Analysis of Maintenance Problems
- Modification Works
- Additional Maintenance Requirements

3.3 HFIR 緊急備品存量 (Critical spare parts) :

a. Nuclear instrument:
   Start up monitor, linear power indicator, log rate indicator, PID servo controller, etc.

b. Process instrument:
   Differential device, transmitter, thermal couple, RTD, alarm setting device, CRT, computer, etc.

c. Mechanical parts:
   Primary pump shaft and impeller (already balanced) x 1,
   CRDM (motor, gear, limit switch, position indicator, etc.),
   Pony motor and shaft, impeller (already balanced) x 1.

3.4 HFIR Overhead Crane Inspection:

The crane crew from ORNL inspect HFIR the crane (50 Ton/ 3 Ton) annually.

3.5 Annual outage duration in HFIR:

- In addition to the routine maintenance (7 days during refueling period) following the end of cycle (23 days full power operation per cycle), there are two special outages in a year. Each one has about 20 days duration in the Spring and Fall time, respectively.
- There are 10 reactor cycles in a year for HFIR.
- The total full power operation days are: 23x10= 230 days.
- The total routine operation days are: (23+7)x10=300 days.
- The total annual outage days are : 20+20=40 days/year.

3.6 HFIR In-service Inspection (ISI) Program:

- According to ASME code section 11, HFIR conducts ISI program every year during annual outage.
- The major outage ISI systems and components are as following:
  a). Primary and secondary system piping welding due to the stress level. (HFIR had performed the stress analysis for their primary and secondary piping system configuration.). 註: {此點不知 TRR-II 是否已納入 EPC bidding?}
  b). Primary pumps, valves, heat exchangers, etc.
  c). Vessel internals such as core support frame, fuel channel, core tank, nozzles, etc.
  d). Pumps, valves performance test: Based on the ASME/ANSI OM-1987 code endorsed by NRC 10 CFR 50; IWV is for valve and IWP is for pump.
- There is a very important swelling phenomena due to neutron transmutation for Al-6061 aluminum material subjected to neutron fluence in the reactor core. So the swelling of all core internal components, beam tubes, etc are the major concerns in ISI program. 註: {鋁合金 Al-6061-T6 輻射腫脹現象, 是未來 TRR-II ISI Program 之重點, 目前結構小組分析結果: The maximum inward deformation of core channel, of 14 mm Al-6061-S-T62 in thickness, due to irradiation swelling for 40 years is 0.0077 mm which is less than the design gap between fuel bundle and inner wall of core channel (1 mm). 但實際輻射腫脹情況, 仍然要靠現場 ISI 檢驗爲準. }
- HFIR 建議本所, 依 ASME Code 及相關法規, 建立 TRR-II 自己的 ISI program. 註: {此點爲 TRR-II 未來維修工作之重點方向. }

3.7 HFIR Rotating machine diagnosis and predictive maintenance program:

HFIR 對其大型轉動機械如馬達, 幫浦, 風扇等訂定預測保養與診斷計畫, 以永久固定之加速度計(Accelerameter)量測振動值後, 轉換成振動頻譜圖, 做爲肇因分析與趨勢分析之依據. 註: {此點 TRR-I 已行之有年.}

肆. HFIR 緊急計畫

4.1 HFIR 緊急計畫區域 (emergency planning zone, EPZ)分析步驟:

HFIR 緊急計畫區域 (EPZ)分析係遵照:
1). 美國 DOE G 151.1 "Emergency Management Guide", August 1997. ORNL/M-2344/V1,
2). DOE G 151.1" Comprehensive Emergency Management System", August 21,1996.
3). HFIR PRA, D.H.Johnson,et.al.,ORNL/RRD/INT-36/R1.
4). HFIR Safety Analysis Report, ORNL/M-2344, Rev. 2.
5). Emergency Planning Zone Document for ORNL, EPZ-95-1-R1, May 1996
6). DOE-STD-1027.92 "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE order 5480.23, Nuclear Safety Analysis Reports", December 1992.
六種文件要求, 並由 HFIR PRA Level 1 analysis and some of Level 2 analysis 分析結果, 找出機率大於 credibility cutoff of 1.0E-6 per year 且會導致 fuel damage 及 radioactive material release 之各項 Scenarios, 再依照這些 Scenarios 做危害分析後可得到不同邊界之 Significant offsite radiological consequence and their estimated doses, which are the important source term(No. of Curie, No. of nuclei) inputs to plug into the EPZ analysis model for the analysis of emergency planning zone.
HFIR 依 EPZ analysis model [ISC(3)ST, which is a industrial source code in Environment Protection Agency] to get their EPZ as 12 miles.
ORNL got an agreement with Tennessee State government that ORNL can only take care of 5 miles for HFIR EPZ, it's the responsibility of Tennessee State government beyond 5 miles.
註: {TRR-II 目前沒有 PRA 分析結果, SAR 亦未定案, 無法做 TRR-II Hazard Analysis, 亦無法做 TRR-II 之 Emergency Planning Zone 分析.

But according to the USA ANSI/ANS15-16-1982 emergency planning for research reactor and USNRC regulatory guide 2.61, the EPZ for 20 MW TRR-II research reactor is 400 meters as described below:

2MW < power < 10 MW	EPZ= 100meter
10MW < power < 20 MW	EPZ= 400meter
50MW < power	EPZ 個別訂定

INER site boundary radius for TRR-II is 291 meters, there is only 100 meters short from 400 meters EPZ required by regulatory guide. In this regard, I discuss with HFIR expert Mr. David Blanchard, Richard Hall, ORNL emergency planning expert Tina Williford in order to save INER's resource to avoid to do the hazard analysis for TRR-II and find out a solution to justify AEC people.}
The only answer is to find a research reactor with the similar type and similar scenarios for the significant consequence and the same probability, to see their EPZ as a reference. But there is no easy EPZ in the world, said Ms. Williford of ORNL emergency response team.

4.3 HFIR EPZ 之訂定程序:

- According to DOE 151.1-1 Emergency Management Guide, Volume 2
- According to the result of HFIR hazard assessment, HFIR worst case accident (Single event that would result in the maximum largest exposure, 又稱 Bounding event) is large break pool LOCA. Its estimated dose at different radius from HFIR, i.e. source term for No. of Curie and No. of nuclei at that boundary, is already known.
- Finding out how far away for the HFIR that the exposure reaches 1 Rem in 2 hours required by DOE Guide (EPZ = 12 miles).

- Backward to HFIR to find out the exposure of 100 Rem for the worst case accident (What point would you have a dose of 100 Rem), according to the hazard analysis model ISC(3)ST, the point is inside HFIR, so the EPZ for 100 Rem is zero.
- According to DOE Guide, EPZ doesn't go beyond 10 miles since it doesn't make sense if it is beyond 10 miles, so just cut it off at 10 miles. Now the EPZ must be somewhere in between 0 and 10 miles.
- Since the accident shows that the exposure is less and less from 5 to 10 miles; and there is an agreement between ORNL and Tennessee State Government, ORNL has limited resources and will take care of only 5 miles emergency planning area, the area beyond 5 miles is the responsibility of Tennessee State Government.
- Based on HFIR offsite consequences and its estimated doses in the hazard analysis report, it is concluded that a nominal radius of 5 miles surrounding HFIR should be defined as the EPZ for the facility.
- So, the HFIR EPZ is finalized to 5 miles from HFIR center.

4.4 HFIR 危害分析(Hazard Assessment)程序:

- Screening of material on a quantitative basis against approved quantity limits or regulations,
- Detailed hazard characterization for those materials not screened out,
- Analysis of possible event scenarios leading to a hazardous release or fuel damage,

- Evaluation of the likely consequences of hazardous materials release.

4.5. HFIR Radiological Event Consequences:

A1: Large break LOCA in reactor pool
A2: Large break LOCA outside reactor pool
A3 – A8: Fuel channel flow blockage (95% of core blockage)
A19: Degradation of primary coolant flow and reactor does scram
A20: Small break LOCA
A21: Heat exchanger tube rupture
B1 – B3: Fire
C1 – C3: Seismic event with primary system not intact
C4 – C6: Seismic event with primary system intact
D1 – D14: Wind (tornado)
E1: Dam or equivalent heavy load dropped on spent fuel racks

4.6. Emergency Exercise and Drill for HFIR:

- 大演習(Five miles EPZ) "Exercise" is been conducted by the ORNL laboratory every year, it might or might not include HFIR emergency evacuation.
- HFIR emergency management program should conduct at least one HFIR exercise annually.
- 小演習 "Drill" is a kinds of small exercise inside HFIR, there are several drills in the HFIR as below:
  1). HFIR portion of Overall ORNL evacuation drill
  2). Shelter-in-place drill
  3). Fire drill
  4). HFIR evacuation drill(疏散小演習)
- HFIR faculty shall conduct an annual drill involving radiological hazards.

職於 2000 年 9 月在 HFIR 實習期間, 適逢 HFIR 年度疏散小演習(evacuation drill), 有幸參與並提出全程觀察請求而獲准, 其演練內容如下:

1). 演習人員以 P/A 廣播演習開始,反應器急停,控制室運轉員將反應器置於 Secured Mode 後, 拔出反應器運轉鑰匙, 所有運轉員由反應器廠房及控制室撤離, 疏散至運轉中心(Operation Center). Plant Manager 在運轉中心負責指揮並清點人數.

2). 反應器廠房內所有工作人員及實驗人員撤離疏散至集合點(Assembly point), 由保健物理人員偵測是否污染, 若無污染則放行至另一集合點. 由專人負責清查人數.

3). 維護人員則疏散至維護工廠會議室成立維護中心(Repair Center), 由維護科長負責指揮並清點人數. 維護人員在維護中心待命支援修護工作.

4). 行政人員, 技術支援人員則留守辦公室(Shelter in place).

5). 演習持續一個小時後結束, 召開會議(Drill Debrief)討論缺失.

4.7 HFIR Emergency Action Level 之分類:

- Operational emergency
- Alert
- Site area emergency
- General emergency

五 HFIR 升級大修計畫

HFIR 升級大修計畫 (HFIR upgrade and outage program) was performed from 10/1/00 to 4/30/2001 for 6 months. 包括下列內容:

1. 預算: 7 million USD for this project.
2. 時程: 10/1/2000 ~ 4/30/2001
3. 工作方式: Work was performed on a 2-shifts, 6 days per week schedule basis.
4. 輻防工安衛生法令依據: According to ALARA, Industry Hygiene and Safety plan, Hoisting and Rigging Lift Plans.
5. 升級大修計畫主要工作項目:

- Permanent beryllium replacement
- Cooling tower replacement(After 35 years operation)
- Rebuild rabbit
- Replace safety related electrical power panel
- Beam tube replacement
- Primary/secondary coolant system piping chemical clean MCC-C and E replacement
- Instrument power transfer switch replacement
- ISI for primary heat exchanger
- Confinement damper replacement
- Control room annunciator system replacement

6. 升級大修計畫任務編組:

- Project Manager- Mike Farrar
- Maintenance Supervisor- Maintenance Manager Ron Crone

- Task leaders- Ed Ducko, Ron Reagon
- Technical experts-
- Operation supervisor- Certified HFIR shift supervisor
- Tooling & material staging-
- Component subject matter experts-
- Technicians

附錄二　京都大學原子爐運轉維修心得

貳.　原子爐簡介

1. 前言

日本京都大學原子爐實驗所校區 (Kyoto University Research Reactor Institute, KURRI) 位於日本大阪府泉南郡熊取市, 現有員工 200 餘人, 包括 21 教授, 24 位助教授; 每年約有 8000 名來自於日本全國, 以及國外大學之物理 , 化學 , 生物 , 醫學 , 藥學 , 工程 , 農業 , 環境等自然科學領域之研究人員, 故該原子爐實驗所係日本全國共同利用之研究所; 每年預算 2,656,380 仟日圓, 現任所長爲井上信教授, 係該所第八任所長.

京都大學原子爐(Kyoto University Reactor, KUR)由日本日立公司設計建造, 其最大熱功率爲 5 MW, 最大熱中子通量爲 $3x10^{13}$ n /sec.cm^2, 冷中子源緩速腔處中子通量爲 $1x10^{13}$ n /sec.cm^2. 京都大學於昭和 36 年(1961 年) 9 月提出原子爐設置申請, 同年 12 月開工 ; 昭和 39 年(1964 年)6 月 25 日首次臨界運轉成功, 同年 8 月輸出功率達 1 MW; 並於昭和 42 年(1967 年) 7 月其輸出功率達額定功率 5MW 運轉. 故其由首次臨界到額定功率 5MW 運轉共費時約 3 年,在 3 年內共計進行安裝實驗設施, 申請運轉執照及提升功率等事宜.

京都大學原子爐實驗所設有中子科學研究部, 核工基礎研究部, 應用原子核科學研究部, 放射線生命科學研究部, 原子爐應用研究部及原子爐醫療基礎研究部等各研究部門. 所長之下另設一直屬單位爲原子爐營運安全管理部, 負責原子爐之計畫管理, 安全運轉, 核燃料管理及實驗設備管理等事宜. 京都大學原子爐實驗所主要實驗設備有四軸型中子散射裝置, 三軸型中子散射裝置, 冷中子實驗設施, 同位素製造設施, 中子活化裝置, 中子捕捉療法裝置, 低溫實驗環路,高溫實驗環路等.

3.　實驗設施

2.1 實驗導管:

3.1 .1 冷中子源設施

京都大學原子爐實驗所冷中子源設施(Cold Neutron Source Facility, CNS)屬於中子科學研究部, 該所冷中子源設施使用液態氘(Deuterium)做爲緩速腔之冷卻劑, 原因爲氘有較小的散射截面(Scattering Cross Section), 可以容許更大的緩速腔體積, 該所之冷中子源設施緩速腔體積爲 4 公升, 內徑 20 公分, 材質爲鋁合金 Al 5083, 因爲鋁合金 5000 系列有較多的鎂含量, 焊接性比鋁合金 6000 系列要好; 但對於鎂含量高的鋁合金 5000 系列, 因爲中子累積通量 (Neutron Fluence) 越多越易造成鎂 Deposition 腫脹變形, 京都大學原子爐功率只有 5MW, 緩速腔處最大熱中子通量僅 $1x10^{13}$ n /sec.cm^2, 照射後沒有腫脹變形之顧率; 但是核能研究所

TRR-II 功率 20MW, 最大熱中子通量高達 $3x10^{14}$ n /sec.cm^2, 緩速腔照射後有腫脹變形之顧率, 所以 TRR-II 使用鋁合金 6000 系列之 Al 6061-T6, 但焊接性較差.建議將由日後 TRR-II 之檢測計畫補強.

2.1.2 低溫照射實驗環路(Low Temperature Irradiation Loop)--- Beam Tube E-4
以液態氮冷卻至 10K° 從事超導體及電晶體方面之研究.

2.1.3 高溫照射實驗環路

2.1.4. 硼中子捕捉療法裝置 (Boron Neutron Capture Therapy, BNCT)--- Heavy Water Thermal Column.
在 Heavy Water Thermal Column 中有 4 個相互隔離之重水槽, 調整各槽之水位可得不同能量之熱中子與 B-10 作用, 並藉著 Prompt Gamma 儀器, 可測定血液中 B-10 之含量, 硼中子捕捉療法裝置之熱中子通量爲 $3x10^9$ n /sec.cm^2. 反應方程式如下:

Thermal Neutron + Boron-10 → Gamma Ray + H_2
Where Gamma Ray Energy : 478 Kev
H_2 Energy : 2.2 Mev, 10% Mass Density.

2.1.5. 中子照相

2.1.6. 冷中子照相:
因低溫(低能量)冷中子有更大的彈性散射截面, 對於 Oil Flow, Water Flow for Bubbling Phenomena in multi-phase flow 可獲得更清晰之照片.

2.1.7. 線上同位素分離設施 (Isotope Separator On Line):
可於功率運轉時, 以二氧化碳氣體帶出分裂產物, 並由 Ge-Li Detector 量測 Prompt Gamma 以分析 U235, Pu239, Am 等之分裂產物同位素含量.

2.1.8. Neutron Mirror Guide and Spin Echo Experiments
2.1.9. Triple Axis Neutron Spectrometer
2.1.10. Four Circle Neutron Diffractometer
2.1.11. Small Angle Neutron Scattering (SANS)

3.2 照射設備
3.2.1 爐心水送管 x1
3.2.2 氣送管 x3
3.2.3 傾斜照射管

3.3 熱中子室
2.3.1 石墨熱中子室 (冷中子源設施)
2.3.2 重水熱中子室 (硼中子捕捉療法裝置)

3. 運轉方式::
京都大學原子爐型式爲輕水緩和與輕水冷卻, 運轉週期四天, 每星期二早上九點啓爐, 星期五下午四點停爐, 其相關運轉重要參數如下:

3.2 燃料 :

- 25 根燃料(包括標準燃料及 5 control rod special fuels) for equilibrium core, 係 MTR-Type 93% 高濃縮 U-Al 合金燃料及 1 根低濃縮 U^3Si_2 燃料.
- 製造廠: Manufactured by KUR 旁邊之 NFI(Nuclear Fuel Industry).
- 標準燃料外觀片狀, Fuel length 873mm, fuel meat 625mm, 重 180Grams for U-235.

- Burn up: 25%, 0.2% reactivity per week. 25x180Gram/core = 4.5 Kg U^{235} per core. There are 3-5 spent fuel elements in a year.

- KUR 用過後燃料必須運送至美國作再處理, 美國規定 KUR 截至 2005 年就不可再用高濃縮燃料.

3.3 控制棒：

- 四根粗調 Shim Rods. Stroke: 67.5cm, Speed: 10cm/min constant speed.
- 一根微調 Regulating Rod. Stroke: 67.5cm, Speed: 1cm/sec constant speed.
- 材質爲硼不鏽鋼合金.
- 控制棒驅動機構位於爐頂, 急停時 Magnetic Power 消失, 靠重力自由落下插入爐心(共需 600 ms, including 50ms mechanical delay for control switch).
- 正常運轉爲 PID Servo Control depends on the difference between linear power and power setting dial to insert into or withdraw from the core.

3.4 中子量測儀器:

3.4.1 Fission chamber x 2 on top of core (Moveable for source range):

- When Log counting rate reach 10^3 cps, 2 fission chambers will automatically withdraw from core in order to save U-235 in the FC.
- When counting rate is less than 2 cps, that means fission chamber is out of order or neutron counting rate is too low after long term shutdown. If it is the later case, then need 2 Curie Am + Be neutron source which is stored in the temporary rack surrounding the core to start up the reactor.

3.4.2 CIC x 2 (Fixed, they are horizontally located on each side outside the core for medium and high power range). One is for Lin- N and the other is for Log- N.

3.4.3 UIC x 2 (Fixed, they are horizontally located on each side outside the core for high power range).Two are for safety power.

3.5 Shutdown Margin:

Delta K/ K is 4 %.

貳. 原子爐運轉詳述

2. 運轉模式:

丙、燃料更換模式: zero power, primary, secondary pumps & cooling tower fans are OFF; NCV open, 4 shim rods and one regulating rod are in the 24 cm position as the Shutdown margin.

丁、自然循環模式: 0 < Power < 100kw, primary, secondary pumps & cooling tower fans are OFF; NCV open, 4 shim rods and one regulating rod are in the bottom position(0 cm). But normally, turn on the primary/secondary pumps and cooling tower fans before start up the reactor.

1.3 功率運轉模式: 100kw<power < 5 Mw, primary, secondary pumps are ON, two CT fans are ON for 100kw <power < 1 Mw, three CT fans are ON for 5 Mw. But normally, turn on the primary/secondary pumps during 出力運轉前檢查表(做完更換燃料 or core reconfiguration/低出力檢查, 冷卻水運轉時) before reactor starts up. When in 5 MW operation, 4 shim rods are in the 37 cm position and regulating rod is in 35 cm position. Reactor period is infinite.

三種運轉模式之間有 key 可以相互轉換.

Suggestion:

Here is a key point I would like to point out that there are only 3 operation modes in KUR as following:

1. Core re-configuration mode,

2. Natural circulation mode,
3. Power operation mode.
I discussed with KUR engineers very often in this regard, they explained to me that:
1). In the core re-configuration mode, it contains two activities which are "refueling" or "supplying" the fresh fuels into temperatory storage rack outside the core, so they called it core reconfiguration instead of refueling mode.
2). In the natural circulation mode, they shutdown the primary/secondary pumps and open the natural circulation valve after reactor shutdown, so they more specifically called it natural circulation mode instead of a general term "shutdown mode".
3). In the power operation mode, their power(5 MW) is smaller compared with TRR-II and they don't have middle power trip point in "rod withdraw error event" as analyzed and suggested by Dr. Yang of TRR-II core analysis group. KUR also uses low power high neutron flux setting and high power(110% full power) setting as their protection system trip point, so they just call it power operation mode.
Comparing current 4 operation modes in TRR-II with KUR control logic suitation, and also considering rod withdraw error in our project, I would like to propose the following 4 modes to replace current operation modes in TRR-II (OPDD):
1). Refueling mode (OPDD: Refueling mode),
2). Natural circulation mode (OPDD: Shutdown mode),
3). Low power mode 0-480KW (OPDD: Startup mode),
4). High power mode 480KW-20MW (OPDD: Power operation mode).
The difference between refueling and natural circulation mode in KUR is the position of control rods. When it is in refueling mode, some of the control rods will be on the top position as a shutdown margin, while it is in the shutdown mode, all control rods will be fully inserted into the core.

JRR-3M has 4 operation modes, refueling, natural circulation, low power and high power modes. Since there is enough excessive reactivity in Jrr-3M, so all the control rods are inserted into the core when refueling.

三、 保護系統急停方式**:**

- Automatic Rundown: Shim rods motors reverse and insert into core. If alarm disappear during automatic rundown, then operator still can increase power.
- Slow Scram (To cut magnetic coil with a time delay relay 10-20 ms before connecting to the magnetic power of shim-rod).
  a). Primary coolant flow rate drops below 80% of nominal rate (Bypass is possible).
  b). Secondary coolant flow rate drops below 50% of nominal rate (Bypass is possible).
  c) When linear power indication exceeds 120% of each range of the power meter.
  d) When core tank level drops by more than 20cm (In this case the primary circulating pump stops).
  e) When any one of the doors of the experimental facilities is opened (Bypass is possible).
  f) When the positive voltage of either of the two CIC power supplies drops.
  g) In case of earthquake is above 0.02 g.
  h) When the natural convection valve is opened (Bypass is possible).
  i) In case of failure of power supplies (Voltage decreases below 90%).
  j) When the manual scram button is pressed.
  k) When the emergency alarm button is pressed.
- Fast Scram(Immediately cut magnetic coil):

(a). When period is less than 5 second (Normal period is 45 second).
(b). When uncompensated ion chamber (UCI) power exceeds 120% of the nominal power or 1200 kw (6MW, 20% full power).
For fast scram, there are two safety power channels for core tank level, primary coolant flow, high temperature, earthquake, etc. All others are single channel monitor.

3 功率調節方式**:**

- 4 shim rods: 67.5 cm stroke, speed is 10cm/min constant speed up and down.
- 1 regulating rod: 67.5cm stroke, with 1 cm/s constant speed up and down.
  - If regulating rod reach off range area (Its upper position), then one of the shim rod withdraw automatically by this signal to make reactor power increase, in order to compensate the reactor power, regulating rod inserts again according to the servo controller, this is called **“Auto Shimming”**.
  The upper off range is 80%, lower off range is 25% for the regulating rod.
  - During reactor shutdown, the “linear power range” meter lamp change its range automatically. This is the same case for reactor start up.
  - Shim rod/ regulating rod position digital indicator(38 cm).
  - Shim rod selectors, A,B,C,D,AC,BD.
  - Shim rod rise inhabit lamp.
  - Regulating rod rise inhabit lamp.
  - Operator can hear the sound of control rods withdraw, insert or falling down in the control room by public system.

4 啓爐前檢查 **:**

4.1 啓爐前檢查測試表(更換燃料/低出力時):

- 4 shim rods position: 4cm. After previous shutdown, it is 4cm higher than bottom to keep CRDM magnet separate from top high humidity region in the core.
- 1 regulating rod position: 0 cm.
- During new fuel loading, withdrawing irradiation capsule for core reconfiguration mode, 4 shim rods and one regulating rod are in the 24 cm position as the shutdown margin.
- Power range selector: 0.3MW
- Energizing the control rods magnetic power in this start up check.
- To initiate a signal to check area monitor to let reactor auto rundown.
- Checking bypass push button(jumper) of protection system.
- Following the check list on the CRT step by step to simulate reactor checking by computer.
- Primary pump is OFF and NCV is OPEN when reactor power is less than 100 kw.(LCO)
- During core re-configuration or natural circulation mode, reactor power has to be less than 300 kw (power range selector is in 300 kw). (LCO).

4.2 出力運轉前檢查表(冷卻水運轉時, ie.做完更換燃料/低出力檢查)

- 做完更換燃料/低出力檢查後, Turn on primary water protection system (Turn off its bypass) and turn off 0.3 MW power range selector.

4.3 定格出力運轉前檢查表

- Put control switch in “Local” position (Normally selecting “Local” switch to start up the reactor).

- Following the checklist on the CRT step by step to simulate reactor checking by computer.
- Start primary/secondary pumps and cooling tower fans. Primary coolant outlet pressure is 0.7 MPa and secondary coolant outlet pressure is 0.343 MPa, secondary motor valve open 76 %.
- NCV will be closed automatically by the pressure head of primary coolant pump outlet.
- Speed measurement for lower down and rising up of regulating rod by three operators, total time for one way is 57 seconds.
- Before reactor starts up, with a check list to check power operation mode, bypass ON, auto power range is 5 Mw (It will take over automatically when reactor power reaches 5 Mw), power range switch is 1 w, etc.

5 啓爐程序:

1). 7/18/00, using public address system to announce before reactor starts up.

2). Put control switch in "Local" position instead of "DCS" position.

3). Manually withdraw 2 sets of shim rods AD or BC in turn to 2 cm first and then to the middle position 34cm (Upper position is 68cm). With two identical but independent log counting rate (LCR) and period meter, readings are as following after 5 minutes:

- LCR reading: 200 cps. Period meter reading: 120 sec, infinite to 45 second.
- Reactor power: 0.3 W.
- Continue lifting 4 shim rods until power reaches 2 W in 2 minutes.

4). Manually withdraw regulating rod to the 26.9cm position (the indicator arrow rotates a revolution when it rising 1 cm). Two fission chambers are still in the lower position. Readings are as below:

- LCR: 10^3 cps. Period: 60 second.
- Power: 5 kw

5). Withdrawing in turn only one shim rod at a time to increase linear power to the desired power, (Only keep on rising shim rod, reactor power then will increase. Otherwise the reactor power will remain unchanged.). Repeat the same procedure to increase reactor power until it reaches 5MW power, 4 shim rods are in 37 cm position and regulating rod is in 35.46 cm position.

6). Selecting "servo controller" for the regulating rod and put in the "DCS" selector.

7). Then the regulating rod will withdraw from or insert into the core by servo-controller depending on the signal difference between power setting dial deviation and the real linear power.

8). The linear power range indicator will change automatically when selecting "Auto Control Mode".

9). The difference between power setting dial and linear power is not allowed to be too large (< 5%) to avoid overshooting.

10). In 5 MW power, 2 fission chamber will withdraw up automatically when counting rate reach near 10^3 cpm. The reason for 2 fission chambers lifted automatically to the upper position is in order to avoid the burn up of U-235 in the fission chamber, 1x 10^6 Japanese Yen for each fission chamber provided by Westinghouse company. LCR reading is 510 cps. LCR is $6x10^3$, period is infinite, 4 shim rods are in automatic shimming status.

11). When reactor power is 5 mw,

- LCR is $6x10^3$cps,
- Period is infinite,
- Linear power: 101.3%

- 公稱出力: 5 MW.
- Log power: 4108kw
- Primary thermal power: 4.98 Mw
- Secondary thermal power: 4.61 Mw
- 安全出力: 4.73 Mw (#5)
- 安全出力: 4.72 Mw (#6)
- Shim A: 60.29 cm
- Shim B: 53 cm
- Shim C: 50 cm
- Shim D: 48 cm
- Regulating rod: 35 cm

12). It only takes 30 minutes to reach 5 MW for the KUR reactor starts up.

13). Operator should write down step by step all important dynamic records during reactor starts up and seal it for taking the responsibility (TRR-I just write down the static records.)

14). On 7/21/00, start up the reactor power to 100 kw for 30 minutes operation for neutron activation experiment, then shutdown for 1 hour:

- 做完定格出力運轉前檢查表
  - Since there is Xenon poison effect due to 7/18/00 shutdown, so the position of 4 shim rods are higher than it was on 7/18/00.
  - 4 shim rods rises to 42.5 cm and the regulating rod rises to 35.42 cm position, keep on in turn rises 4 shim rods until 43.75 cm position (power will increase according to the rising of shim rod. If shim rod stops, then power will accordingly keep at a unchanged value.).
- Withdrawing in turn only one shim rod at a time to increase linear power to desired power, (Only keep on rising shim rod, reactor power then will increase. Otherwise the reactor power will remain unchanged.). Repeat the same procedure to increase reactor power until it reaches 100 kw power, 4 shim rods are in 43.75 cm position and regulating rod is in 35.42 cm position.
- Selecting “servo controller” for the regulating rod and put in the “DCS” selector.
  - Put the deviation meter in 1 % deviation.
  - 2 fission chambers automatically rise to 46% and 70% position from the bottom, respectively. (# 1 is 3087 cps, # 2 is 3000 cps).
  - 4 shim rods are in automatic shimming status.
- Period is infinite,
  - Linear power: 101.%
  - 公稱出力: 100 kw.
  - Log power: 82 kw
  - Primary thermal power: 98 kw
  - Secondary thermal power: 95 kw
  - 安全出力: 0.1mw (#5)
  - 安全出力: 0.1mw (#6)
  - Shim A: 43.75 cm
  - Shim B: 43.75 cm
  - Shim C: 43.78 cm
  - Shim D: 43.00 cm
  - Regulating rod: 34.57 cm
- It only takes 20 minutes to reach 100 kw for the KUR reactor starts up.

- Operator should write down step by step all the important dynamic records during reactor starts up and seal it for taking the responsibility.
- Prof. Mishima tell me that operator should use natural circulation mode for 100 kw power operation today if it is the neutron flux measurement experiment inside the core to avoid disturbing of primary coolant flow in core.

6. 停爐程序:

Put the control mode in the “Local” position instead of the “DCS” position. 手動選擇四根粗調 Shim Rod 同時自動下降插入爐心(On top of reactor, we can see and hear the 4 shim rods falling down into core with the speed 10 cm/min for 4 shim rods and 1 cm/sec for regulating rod), 此時反應器功率由 5MW 迅速降爲 50KW(It takes only 1 minute), 四根粗調 Shim Rod 全入後, 手動選擇微調 Regulating Rod 下降插入爐心, Regulating Rod 全入後, 反應器功率已達零功率(0.1kw 以下, period is –200 second, -262 second is almost infinite), 全部停爐過程只需 15 分鐘即可完成.

反應器停爐後, 要依步驟做停爐點撿, 將控制棒驅動機構磁鐵電源鎖匙, Local/DCS 轉換鎖匙, 控制電源鎖匙, 保護系統控制面盤鎖匙拔出, 並將運轉模式鎖匙置於自然循環位置後拔出(共五支鎖匙), 關閉 Recorder, Chart, Start up Monitor 電源, 並將 4 shim rods position 升置 4.18cm 位置(將 CRDM 避開爐頂上方 high humidity region), 2 Fission chamber 自動下降到底, 停止主冷卻水 Pump,次冷卻水 Pump 及三台冷卻水塔風扇運轉, 自然循環閥自動打開後即完成所有停爐程序.

停爐後僅維持下列設備運轉:

- Spent fuel clean up pump
- Primary clean up pump
- Sweep gas blower
- Cooling tower pump
- Secondary pressurizer.

註: 京都大學原子爐自然循環閥之設計在若干年前也是手動操作, 但目前已完全自動, 其原理爲停止主冷卻水 Pump 後其出口壓力消失, 原先被該出口壓力經一迴路頂上去的閥桿, 自由落到定位而產生一流體通路, 造成自然循環閥自動打開, 爐底之水向上流動形成爐心自然循環.

停爐點檢測試表 is on the display monitor, operator conducts the shutdown procedure step by step according to the “停爐點檢測試表” to finish the reactor shutdown.

5 **廠區巡視抄表(Building Check):** 1 time per shift, 2 times per day, 9 AM and 20 PM.

6 中子量測方式:

1). Source range: 2 Fission Chamber, 1 cpm to 10^3 cpm.
  2 FC will withdraw from the core automatically when counting rate reach near 10^3 cpm.
  To avoid 2 FC withdraw at the same time (Can’t monitor reactor power).
2). Intermediate range: CIC.
3). High power range: Uncompensated ion chamber

7 燃料操作方式:

9.1 新燃料操作

- For new fuel, before loading into a temporary rack in core, operator has to take the new fuel from new fuel storage office under the supervision of Prof. Mishima who has the key and digital code to open the office.
- There is a series number on the surface of the new fuel element.
- For new fuel, before loading into a temporary rack surrounding the core for 4 weeks before loading into core, before loading into the temporary rack, operator has to shake the fuel in the core pool since there's thin foil on the surface of fuel which may fluctuate the reactor power.
- For new fuel loading into temporary rack, there is a special tool handle, by coupling the handle to the cork, operator can revolve the rack circularly to pinpoint the rack position. The shift supervisor inspects the core by a telescope.

- Using special handle to close the top core shielding.
- Overhead circular crane move circularly (not translationally) in the confinement building.

9.2 用過燃料操作

For spent fuel, after burn up reach 25%, withdraw the spent fuel to the temporary rack for 40 days to cool down, then use transfer tube and canal to transfer SF rod to spent fuel pool (5 x 6 x 7m depth, total volume is 470m^3). In average, there is only one spent fuel generated per year, the fuel cycle in core is also one year.

- Withdraw all control rods in the 24 cm position as the shutdown margin.
- By using a long handle tool, operator clamps the SF rod (another operator uses a binocular to confirm the SF rod position), put the rod onto the transfer tube and engage.
- Open the canal valve in the first floor by a long handle tool.
- With the cable driven by a pulley, the transfer device hang up the spent fuel rod and lower it down to the cart in canal on the first floor, speed is very low.
- By using a rope, operator pull the cart through a canal to spent fuel pool outside the confinement, and the canal is inside the confinement.
- by a long handle tool, operator clamps the spent fuel rod and put it on the temporary storage rack.
- In the previous time, all above procedures are operated automatically, but it had too many troubles, so KUR changes it to manually operate now.

9.3 照射過樣品棒操作

- Basically, the procedure is the same as spent fuel rod transfer, after the long term irradiation capsule rod(same size as fuel rod) has been moved to the spent fuel pool, operator take out the capsule and transfer it to experimental cave beside the spent fuel pool by a canal. All jobs are underwater by using an underwater lamp which lifetime is only 30 hours.
- After taking out the capsule from the sample rod, operator put the sample rod back to the cart, using rope to pull up to and engage the transfer device in canal on the first floor.
- Operator on top of the core operates the pulley to raise the sample rod to the core tank by cable.
- Using a long handle tool to clamp the sample rod from the transfer device and move it to the core (another operator uses a binocular to confirm the spent fuel rod position).
    - With a special cover to cover the fuel transfer tube in the core tank.

- With a special design tool to close the top shielding of the core.

8 系統廠房:

1). Primary Pump x 3:

- Two of them are driven by 440V 60KW offsite power, one is driven by 75KVA CVCF (UPS) for 30 second (By Japanese Regulation), actually 45 second to keep core flow and avoid lower than 150% CHF.
- Normal flow rate is about 900 m^3/hr and pressure is 0.26 MPa.

2). Secondary Pump x3:

- 2/3 operation, all driven by 440V 60 kw offsite power.
- Normal flow rate is 630 m^3/hr and pressure is 0.34 MPa.

3). Cooling Tower Fan x3.

- Cooling tower supply water is 10 m^3/hr.

4). Core flow: 100 m^3/hr.

5). HVAC System:

- Intake and exhaust ducts of reactor building have water seal to avoid radio-nuclide leaks out of confinement during emergency.
- The emergency fan flow rate is 10 m^3/min to keep pressure lower than atmosphere.
- The normal pressure inside reactor is 0.5kPascal lower than atmosphere.
- There is no vacuum breaker in KUR.
- KUR confinement leakage rate test is conducted by STA(日本科技廳原子力管制局) each year.

6). NCV:

- NCV will be opened automatically due to loss of primary flow head after turning off the primary pump during reactor shutdown.
- Close NCV when reactor power is 100 kw.
- If NCV has been opened during reactor operation, then reactor will scram.

7). There is no auxiliary pump in KUR.

9 Earthquake Requirement:

Design earthquake is 0.6 g, scram earthquake is 0.02 g (20 Gal, 1g = 980Gal).
Kobe earthquake: 200-250Gal, 1/17/1995, 5:47AM.

10 主控制室:

1). 計 4 台 Identical but Independent Monitor to digitally display and alarm all essential signals.

2). Primary pumps/valves, secondary pumps/valves, cooling tower fans, primary and spent fuel cleanup system pump, NCV, hot sump and cold sump pump, etc control and indication.

- All pump switches in MCR has plastic cover for the “stop” switch to avoid false push the button during power operation.
- All process control and flow chart display are in the control console, there is no large display panel in the control room.

3). Three operation modes: Fuel reconfiguration, natural circulation and power operation, its selector and indicator.

4). “DCS” or “Local” control mode transfer key.

5). Shim rod and R-rod control switch and indication.

- - Shim rod/ regulating rod position digital indicator (e.g. 38 cm).
- Shim rod selectors, A, B, C, D, AC, BD.
- Shim rod rising inhabit lamp.
- Regulating rod rising inhabit lamp (When rising shim rod, this lamp light).

6). Control rods position digital indication.
7). Power range selector: 1 w, 10 w, 100w, 10kw,…1Mw, 5Mw.
8). Capsule position, CO_2 valve (pneumatic tube), Pn emergency return.
9). Auto shim, deviation range (15 %), Servo control.
10). Control power, magnetic power and recorder power.
11). All protection system scram signal: Fast scram, slow scram and automatic rundown.
12). Linear, Log Counting Rate (LCRx2), period indication.
13). Alarm signal is described on the display monitor digitally, operator can see and acknowledge the alarm.
14). Area monitors:

- B-1 通路, B-4 通路, TC 通路, D2O 通路, E-3 shielding, Fuel storage pool,
- MCR, ion exchanger room(5mr/h), basement experiment, 爐頂 (5mr/h).
- IX column 1 ($8x10^2$ cps), IX column 2, 爐頂(Beta, Gamma),

15). Microphone: Push button default public address system.
16). Emergency push button (plastic cover).
17). Emergency water injection valve (plastic cover).
18). Scram reset, Reset, Acknowledge (Also acknowledge in the CRT of display monitor).
19). Protection system relay and connector.
20). All important tanks level such as core tank, spent fuel pool, sub-pool, hot tank, cold tank, etc.
21). There is no door key for the control room in KUR.

11 爐體:

- With a cover shielding which is operated manually by a special design handle on the top of reactor core, also there is a small observation hole in the cover shielding.
- Without decay tank, without thermal layer.
- Without core tank leakage detecting system.
- KUR core tank material is Al-5052, 2m in diameter, 8m in height, 12mm in thickness.

12 首次臨界啓爐程序:

In 1964, KURRI Prof. Fujita used 2 BF_3 counters and 2 Fission Chambers to detect the five 2 Curie Am^{241}+Be neutron sources which are in pullet form inside stain-steel capture, one of them was installed in KUR hydraulic convey and other 4 are put in the slant exposure tube.
The first criticality timing was described as in the 1967 KUR annual report:

- After 5 special fuels and 6 standard fuel elements had been inserted into the core.
- 4 shim rods and 1 regulating rod are in the upper position.
- Constant linear power recorder was recognized, in other words, the reactor reached critical condition, the amount of U-235 loaded at that time was 3,0597.7 Gram.

Mr. Ishihara: The BF_3 is not stable due to their strong gamma ray ionization, but BF_3 sensitivity is 10 times better than Fission Chamber. So in the first criticality, KUR used BF_3 as well as fission chamber as the neutron detector.

13 長期停爐後啓爐程序:

- Normally, KUR will shutdown for almost a month in August, so, after shutdown for a month or two, operator will use Am+Be neutron source which is stored in the core tank temporary rack to start up the reactor, and also use 2 fission chambers as the counter.
- For current KUR, since there are a lot of dirty material which is gamma emitter inside the core, BF_3 counter will be affected by gamma ray, so KUR doesn't use BF_3 counter for their start up after long term shutdown.

16. 備用停機面盤(Alternative Shutdown Panel):

There is an emergency scram push button and radiation level, high temperature, earthquake indicator in central management office(中央管理室).

17. Tritium concentration limit in KUR:

Tritium is Beta decay with 18Kev and 12.5year half life. As the reactor is operated, part of the deuterium in heavy water system absorbs neutron to turn into tritium, so the amount of tritium in heavy water system will increase gradually. As a result for measurement of tritium in heavy water by a scintillation spectrometer at the time of initial loading, it was found to be 0.0033 uc/ml on August 1,1962, which agreed with the result of measurement carried out at USAEC. After reactor operation, the amount of tritium in heavy water was known to be approximately proportional to the total operation power of reactor, increasing at the rate of 0.06 uc/ml/MWD. The measurement data were as below:

Total reactor power	Tritium amount(uc/ml)	Date
36KWH(-0.0 MWD)	0.0033	7/20/1964
24,227KWH(1 MWD)	0.069	8/18/1964
120497KWH(5MWD)	0.33	8/23/1964
347512KWD(14.5MWD)	0.84	3/26/1965

- KUR does not have heavy water in the core tank, and there is only little heavy water (2000 liter = 2 m^3 in total) in the thermal column for the production of thermal neutron guide tubes(e.g. BNCT), so KUR doesn't know the limit of T^3 concentration in their heavy water system. The chief supervisor Dr. Cobayashi said that in HFBR people of Brookhaven National Lab replace the old heavy water by pushing fresh D_2O into system in order to reduce the T^3 concentration.
- According to the measurement of KUR, Tritium concentration is 210 uc/cm^3 now, so for total 2 m^3 D_2O, it is $(2x10^6)$ x 210 = 420 Ci, so it is 420Ci /2000 liter = 0.21 Ci/Liter for KUR Tritium concentration now.
- KUR follows the STA regulation: For radiation protection reason, the upper limit of radioactive gas concentration is 370 mBq/cm^3.
- KUR measures tritium concentration by taking sample from air in the D_2O thermal column of confinement. Normally the value is 2-8 Bq/cm^3 for tritium in the air, the alarm value is 10 Bq/cm^3.
- As a support information, NIST are limited to no more than 5 Curies per liter of tritium in their heavy water, based upon a possible leakage analysis related to the Technical Specifications, NIST actually restrict it to less than 2 Ci/l.

18. 廠區安全 CCTV:

- 爐頂
- 雙重氣密門

- Heat exchange room
- Core

19. 運轉訓練編組人力**:**

19.1 KUR 運轉人力:

- 7 shifts in a week, 12 hours per shift.
- 5 persons per shift. (1 shift supervisor, 4 reactor operators)
- 2 persons in control room per shift(Required by Japanese Regulation).
- 1 person in central management office.
- 1 chief supervisor per research reactor. (Required by Japan Science and Technology Agency regulation). There are 7 chief supervisors in KURRI until now.
- There are 30 people in KUR operation and management division (including fuel people).

19.2 KUR 運轉訓練人力:

2 人, 訓練 6 months.

20. 試運轉及熱試車項目**:**

1.Primary cooling system performance test.
2.Secondary cooling system performance test.
3.Power calibration 核出力測定試驗
4.Thermal neutron flux distribution 測定試驗
5.Measurement of temperature coefficient of reactivity.
6.Temperature coefficient measurement by local heating.
7.Temperature distribution on fuel plate surface.
8.Heat transmission rate of heat exchanger.
9.Measurement of neutron flux and gamma dose of experimental facilities.
10.Radioactivity in primary cooling water measurement for Na-24, N-16 and Argon-41.
11.Measurement of Tritium production in heavy water system.
12.Deutrization of ion exchange resin for heavy water clean up and radioactivity of heavy water.
13.Test of reactor confinement.

21. 總運轉時數與燃耗度 **:**

- 180 gram U-235 per fuel element.
- 1 gram burn up = 1 MWD.
- 25% burn up per fuel element.
- 180x0.25 = 45gram per fuel element can burn up = 45 MWD
- KUR is operated for 70-80 hours per week = 2000 hours per year operation = 420MWD = 420 gram burn up in total per year.
- There are 25 fuel elements in core, 25 x 180 gram = 4.5 Kg U-235 per core.
- 420 gram / 4.5 Kg = 10% spent fuel per core per year, that is 25 x 10% = 2.5 spent fuels per year.

22. 實驗設施與控制室界面

進入控制室之實驗設施急停信號如下:

- Cold Neutron Source Abnormal,

冷中子源實驗設施共有三個急停信號, 結合成一個急停原子爐之信號進入控制室. 三個急停信號如下:

1). Deuterium gas buffer tank pressure high/low for reactor automatic rundown scram:

甲、Kg/cm^2 for low limit.
4.5 Kg/cm^2 for upper limit.
2). Pressure of vacuum chamber high (Vacuum chamber 真空度):
There is an alarm signal when it reaches 10^{-4} Torr (It indicates that there is air leaks into the vacuum chamber, it is 10^{-7} Torr normally).
There is an automatic rundown scram when it reaches 10 Torr for the vacuum chamber pressure.
3) When the reactor is ON and CNS is OFF, vacuum chamber is filled with Helium gas to remove the gamma heating and cooling for the moderator cell, the normal pressure for He gas is 150 Torr to make sure the moderator cell temperature is less than $125C^0$(Otherwise there is Al-5083 Mg deposition to initiate the crack), when the He gas pressure is as low as 25 Torr, there is an alarm signal in the reactor control room and results in an automatic rundown scram.

- Low Temperature Loop Abnormal,
- Experimental Beam Tube Door Open

參. 原子爐維修:

- FCDM: Fission Chamber Drive Mechanism is maintained by KUR and other contracted private company together.
- Technician office(技術室): responsible for all the maintenance activity in KUR.
- 緊急備品存量(Critical spare parts) :

d. Nuclear instrument:
Start up monitor, linear power indicator, log rate indicator, PID servo controller, etc.

e. Process instrument:
Differential device, transmitter, thermal couple, RTD, alarm setting device, CRT, computer, etc.

f. Mechanical parts:
Primary pump x 1, CRDM (motor, gear, limit switch, position indicator, etc.), small valve.

肆. 緊急計畫:

1999 年 9 月 30 日, 在日本東海村 UF6 燃料轉化工廠臨界意外事件發生後, 日本 Science and Technology Agency 才要求研究用反應爐要有緊急對策(Emergency Planning), 目前 KUR 正在建立研究用反應爐緊急對策.

g. STA requests KUR to have 500meter EPZ according to the STA regulation for reactor power between 100kw and 10 Mw,

h. KUR estimates their EPZ in two postulated accidents to be 300meter for his 5Mw reactor, Prof. Fujita said it is very consistent with STA's requirement.

i. The distance between KUR and its main gate is about 300 meter.

j. According to the USA ANSI/ANS15-16-1982 emergency planning for research reactor and USNRC regulatory guide 2.61, the EPZ is as below:
2MW < power < 10 MW EPZ= 100meter
10MW < power < 20 MW EPZ= 400meter
50MW < power EPZ 個別訂定

k. KUR still wants to use 500meter as their EPZ.

五. 京都大學原子爐冷中子源設施:

5.1 特性說明:

京都大學原子爐實驗所冷中子源設施(Cold Neutron Source Facility)屬於中子科學研究部, 建造於 1986 年, 爲日本第一座冷中子源設施. 該所冷中子源設施使用液態氘(Deuterium)做爲緩速腔之冷卻劑, 原因爲氘有較小的散射截面(Scattering Cross Section), 可以容許更大的緩速腔體積, 該所之冷中子源設施緩速腔體積爲 4 公升, 內徑 20 公分, 材質爲鋁合金 Al 5083, 因爲鋁合金 5000 系列有較多的鎂含量, 焊接性比鋁合金 6000 系列要好; 但對於鎂含量高的 5000 系列, 因爲中子累積通量 (Neutron Fluence) 越多易造成鎂 Deposition 腫脹變形, 京都大學原子爐功率只有 5MW, 最大熱中子通量 $3x10^{13}$ n /sec.cm^2, 緩速腔熱中子通量僅 10^{13} n /sec.cm^2,沒有腫脹變形之顧慮; 但是 TRR-II 功率 20MW, 最大熱中子通量高達 $3x10^{14}$ n /sec.cm^2, 有腫脹變形之顧慮, 所以使用鋁合金 6000 系列之 Al 6061-T6, 但焊接性較差.

京都大學原子爐實驗所冷中子源設施雖使用液態氘做爲緩速腔之冷卻劑, 可得較小的散射截面, 但氘易被中子活化產生氚氣是其缺點, 故核能研究所 TRR-II 使用液態氫做爲緩速腔之冷卻劑.

冷中子之定義爲 Wavelength 大於 4 A 之中子, 可用於研究材料結構或相位轉換臨界點之變化現象.並可進而由冷中子製造出非常冷中子(Very Cold Neutron, VCN, Wavelength :30-300A))及極冷中子(Ultra Cold Neutron, UCN, Wavelength >580A)以應用於基本物理研究領域.

一般研究用原子爐之冷中子密度僅佔其熱中子分佈之 1% - 2%, 必須使用冷卻劑冷卻緩速腔以獲得 Wavelength 大於 4A 之冷中子.相較於固態之緩速體, 因爲液態氘及液態氫有穩定之截面以移除 Gamma Heating 並減少輻射傷害, 故仍被使用於冷中子源設施.

京都大學原子爐實驗所冷中子源設施安裝於原子爐石墨 Thermal column(1.5m x 1.5m x 2m depth)內, 在原子爐側並有 20cm 厚之鉛熱屏蔽, 以降低 Gamma Ray 及冷中子源 Gamma Heating. 另有裝置預防氘氣洩漏及空氣進入氘氣系統造成暴炸. 日本 Nippon SANSO 公司有技術非常優良之焊工可以焊出厚度極薄之緩速腔.

5.2. 冷中子源實驗設施原子爐急停信號:

冷中子源實驗設施共有三個急停信號, 結合成一個急停原子爐之信號進入控制室. 三個急停信號如下:

1). Deuterium gas buffer tank pressure high/low for reactor automatic rundown scram:

1.0 Kg/cm^2 for low limit.

4.5 Kg/cm^2 for upper limit.

2). Pressure of vacuum chamber high (Vacuum chamber 真空度):

There is an alarm signal when it reaches 10^{-4} Torr (It indicates that there is air leaks into the vacuum chamber, it is 10^{-7} Torr normally).

There is an automatic rundown scram when it reaches 10 Torr for the vacuum chamber pressure.

3).When the reactor is ON and CNS is OFF, vacuum chamber is filled with Helium gas to remove the gamma heating and cooling for the moderator cell, the normal pressure for He gas is 150 Torr to make sure the moderator cell temperature is less than $125C^0$(Otherwise there is Al-5083 Mg deposition to initiate the crack), when the He gas pressure is as low as 25 Torr, there is an alarm signal in the reactor control room and results in an automatic rundown scram.

5.3 冷中子源設施起動前檢查項目**:**

1. 非操作時檢查確認(非操作時一週檢查兩次).
2. Logbook 異常狀況確認.
3. Operation plan 確認.
4. Purity of Deuterium gas 確認.(< 25 ppm), if air intrudes, then its purity will exceed 100 ppm).
5. Purity of Helium gas in the refrigerator 確認.(< 25 ppm, if air intrudes, then its purity will exceed 100 ppm, N_2, O_2, CO_2).
6. Control panel alarm clear.
7. Interlock key is ON (so CNS alarm signal can be transmitted to the reactor control room).
8. Deuterium gas pressure of buffer tank is between 3.0 Kg/cm^2 G and 3.8 Kg/cm^2 G.
9. Constant volume pressure of Helium gas in the vacuum chamber (It is filled with He gas to cool down the moderator cell, 140 – 150 Torr).
10. Control panel CVCF (it means UPS) is OK.
11. Pocket bell alarm system is OK.
12. Hydrogen release alarm system (There are 6 detectors in the reactor confinement).
13. Deuterium gas shutoff valve is open (When emergency, we can save Deuterium gas in the reactor building if close this valve).
14. Fire alarm system is OK.
15. The pressure of helium gas to compressor (3.3 –3.7 Kg/cm^2 G).
16. Primary helium gas release pressure (For Deuterium gas release, >100 Kg/cm^2 G).
17. Secondary helium gas release pressure (Helium gas is released to reactor stack with Deuterium gas).
18. Emergency helium supply system valve is open.
19. Compressor room temperature.
20. Helium gas pressure for the condenser and helium transfer tube (> 11 Kg/cm^2G).
21. Valve opening to control helium gas into the vacuum chamber (Opening is 70%).
22. The pressure which supplies helium gas to moderator cell (0.2 –0.4 Kg/cm^2G).

5.4 冷中子源實驗設施起動程序**:**

1. 起動 Cooling water system.
2. 起動 Cooling tower water system for the helium compressor and refrigerator.(There is no such system in our TRR-II system since we use reactor service water as the cooling tower system).
3. Check the CNS automatic rundown scram function is normal in the reactor control room.
4. Start the rough (Rotary) pump to evacuate the existing helium gas in the vacuum chamber, it will take 1 hour to reach < 3 x 10^{-1} m bar pressure (The vacuum chamber is filled with helium gas when CNS is OFF, its pressure is 140 Torr).
5. Start turbine molecular pump until it reaches < 1 x 10^{-5} m bar.
6. Using mass spectrometer to analyze the impurity gas content in the helium gas system, to make sure that there is no air intruding into the helium gas system.

{The emission current is 5 mA and the sensitivity are 10^{-9} and 10^{-10}, respectively to distinguish the mass number for 4(He, D_2), 20(Ne), 28(N_2), 32(O_2), 44(CO_2)}.

This gas analyzer system is very important for monitoring the leakage of helium gas system, but there is no plan for this system for TRR-II until now.

7. 起動 helium gas compressor (Screw type) to compress and adjust helium gas into the refrigerator and then the moderator cell (It will always keep the inlet pressure of the compressor above the atmosphere, otherwise air is easily to enter the helium gas system).
8. 起動 Refrigerator, control turbine speed and helium flow rate in order to force helium gas into the refrigerator and then the moderator cell.
9. Refrigerator 起動後 5 小時, 其出口溫度達 100 K, 此時起動輔助真空抽氣 ion pump, vacuum chamber 之真空度可抽至 1.9 x 10^{-7} Torr.
10. Refrigerator 起動後 14 小時, 其出口溫度達 24 -28 K, 此時低溫狀態指示燈亮.
11. With PIC (Pressure Indication Control) to control the pressure of deuterium gas in buffer tank at 2.2 Kg/cm^{2}G (Setting value is 1.95 Kg/cm^{2}G).
12. Waiting for reactor full power operation.

5.5 冷中子源實驗設施起動注意事項**:**

1. Cold neutron source is always started before reactor starts up.
2. It needs 4 hours for evacuating the vacuum chamber and 1 hour for the safety check, it also needs another 6 hours for introducing deuterium gas into the moderator cell, so it is suggested that we start the cold neutron source facility one day ahead of the reactor start up.
3. Vacuum chamber 低真空計 PR-V102 (Low pressure gauge, 10 – 1020 m bar) is a diaphragm displacement/electrical resistance type pressure gauge, by measuring the resistance change due to the displacement change, we can find the pressure change. It is not filament type which is not endurable.
4. Vacuum chamber 高真空計 PR-V101 (Low low pressure gauge, <10^{-2} m bar) is a 500 volts and plate cathode type pressure gauge, very endurable for 15 years usage).
5. There is no pressure resistance for buffer tank pressure, moderator transfer tube pressure and moderator cell pressure in a second range (There is a pressure resistance in 100 msec range).