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出國報告（出國類別：其他）

赴美國 Zachry 公司進行圍阻體分析工作及 AREVA 公司審查燃料再填換分析工作

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派赴國家：美國
出國期間：102 年 7 月 8 日~102 年 7 月 28 日
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摘　要

本所核工組於執行台電公司委託之「核二廠中幅度功率提昇技術服務案」中有牽涉到圍阻體熱流分析工作，且在「龍門電廠圍阻體熱水流分析方法論法制化與應用」中，與 Zachry 公司合作進行 GOTHIC 程式相關分析工作，依合約本所須派員赴該公司 Numerical Applications 部門(位於美國華盛頓州里奇蘭市)進行相關工作，本所指派核工組工程師苑穎瑞、助理研究員陳彥旭、助理工程師林金足等三員赴 Zachry 公司 Numerical Applications 部門進行圍阻體熱流分析相關工作，工作期程為 7 月 9 日至 14 日。

核工組所執行之「核二廠中幅度功率提昇技術服務案」計畫中，也委請核二廠的燃料廠家 AREVA 公司進行二號機在中幅度功率提昇(Stretch Power Uprate, SPU)條件下，週期 23 中(Middle of Cycle, MOC)燃料再填換分析(Reload Licensing Analysis, RLA)的相關工作，台電公司已承諾原能會於今年 8 月陳送該份 RLA 報告進行審查，為配合規畫時程，本所指派前述三員，赴同樣位於里奇蘭市的 AREVA 公司進行 RLA 報告初稿審查工作。同時，為執行「沸水式反應器爐心佈局優質設計自動搜尋系統之開發與應用」計畫，另指派核工組副研究員童武雄同行以討論核二廠爐心佈局設計優化技術，工作期間為 7 月 15 日至 25 日。

本次出國在 Zachery Numerical Applications 部門方面，該公司已進行及完成本所所提 GOTHIC 程式執行上之各項問題澄清與答覆，同時本所亦與該公司進行 GOTHIC 應用分析方面之技術與使用經驗交流。在 AREVA 中幅度功率提昇再填換燃料分析(RLA)方面，出國同仁於停留該公司期間，已針對核二廠二號機週期 23 RLA 涉及之各項分析，進行實質之計算審查，包括中子分析、熱水力分析及機械分析等領域，同時提出 33 項審查意見，該公司針對此審查意見與出國同仁充分討論與澄清，最後做出書面回覆，並對 RLA 報告依據審查意見作一些修訂，於今年 7 月底提出定案版本。在爐心佈局設計優化技術方面，也獲得了許多寶貴的意見。因此整體而言，此次出國已達成既定之任務與目標。

關鍵字：核二廠中幅度功率提昇、燃料再填換分析、圍阻體熱流分析。

目　　次

一、目　的

(一)本所承接台電公司委託計畫「核二廠中幅度功率提昇技術服務案」中有牽涉到圍阻體熱流分析工作，並在「龍門電廠圍阻體熱水流分析方法論法制化與應用」中，本所與 Zachry 公司合作進行 GOTHIC 程式相關分析工作(合約 FL1011350)，依合約本所須派員赴該公司 Numerical Applications 部門(位於美國華盛頓州里奇蘭市)進行相關工作，期程為 7 月 9 日至 14 日，此項工作人員包括苑穎瑞、陳彥旭、林金足等三員。

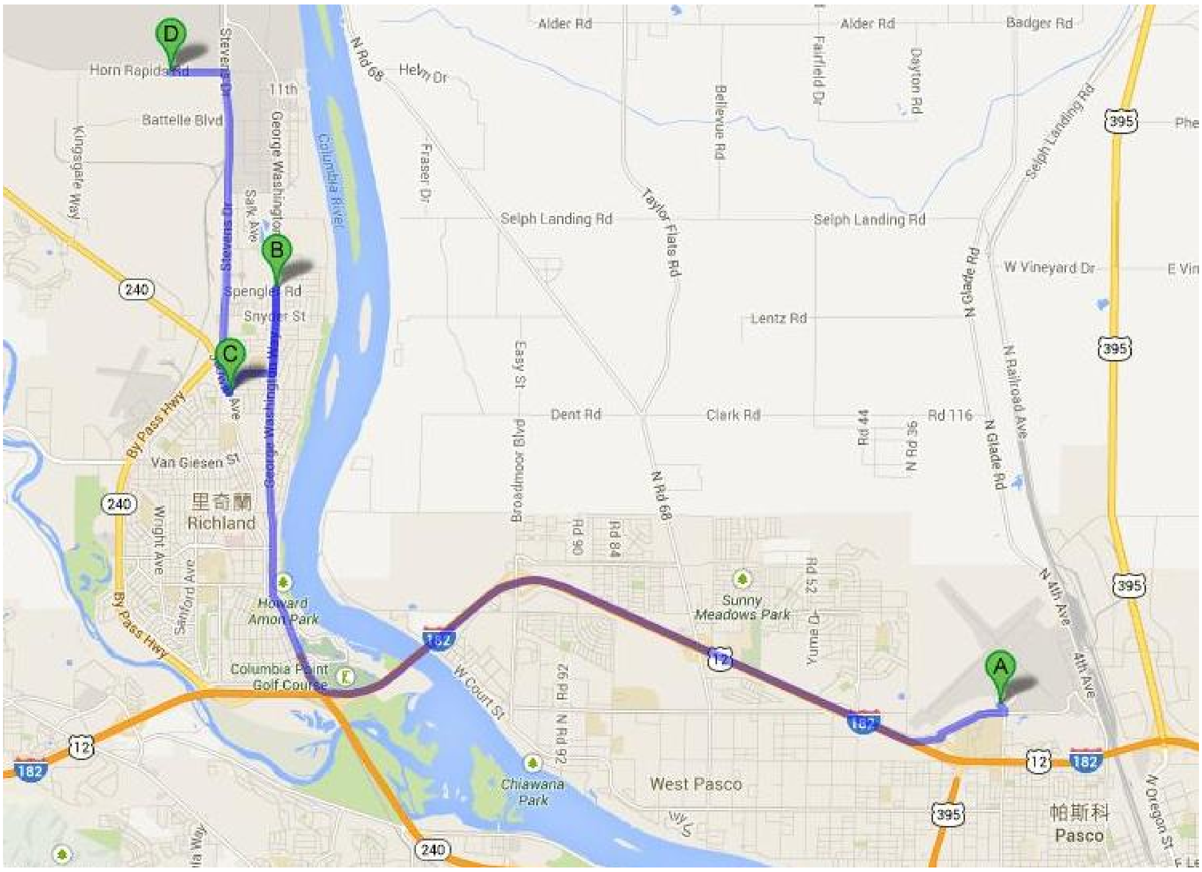
(二)此外，在本所承接委託計畫「核二廠中幅度功率提昇技術服務案」中，本所委託 AREVA NP 公司進行中幅度功率提昇(SPU)條件下，核二廠二號機週期 23 MOC 燃料再填換分析(Reload Licensing Analysis, RLA)相關工作(合約 FL1011238)。分析結果初稿預定於 7 月 31 日完成，依合約本所須派員赴 AREVA NP 公司(位於美國華盛頓州里奇蘭市)進行審查工作，以配合預計於今年 8 月將完稿陳送原能會審查之規畫。此外，將與 AREVA 討論「沸水式反應器爐心佈局優質設計自動搜尋系統之開發與應用」計畫發展之核二廠爐心佈局設計優化技術，期程為 7 月 15 日至 25 日，此項工作人員包括苑穎瑞、童武雄、陳彥旭、林金足等四員。

二、過　程

(一)本次公差行程說明

本次公差兩目的地 AREVA 公司與 NAI 公司皆位於美國華盛頓州的里奇蘭市，該市與其臨近之 Kennewick 及 Pasco 市合稱為 Tri-cities。苑員、陳員與林員三人於 7 月 9 日抵達里奇蘭市，於 7 月 9 日至 14 日赴 NAI 公司。童員另於 14 日抵達里奇蘭市，四員於 7 月 15 日至 25 日赴 AREVA 公司進行工作。

AREVA 公司與 NAI 公司位置如圖二-1 所示，圖中 A 為 Pasco 市 Tri-Cities 機場，B 為住宿地點，C 為 NAI 公司，D 為 AREVA 公司。



圖二-1 本次公差前往之 Richland City

(二) Zachry 公司 Numerical Application 部門(NAI)圍阻體分析應用工作

Zachry 公司的 Numerical Applications 部門原本是獨立公司 Numerical Applications Inc.

(簡稱 NAI)，該公司發展之核能相關分析程式，包括 GOTHIC、CentralStor 及 RADTRAD-NAI，已有相當數量使用者，亦有不少美國電力公司使用其程式分析結果，向核能管制委員會申請相關應用或安全分析工作。

NAI 已成立超過二十年，位於美國華盛頓州里奇蘭市(Richland, WA)的 Jadwin Avenue，原本核心成員是以 COBRA 程式的技術與經驗為基礎，發展出核電廠圍阻體分析程式 GOTHIC，經逐漸改良後，目前 GOTHIC 已是國際間最新之圍阻體分析程式，且因其應用彈性大，使用介面也較早期分析程式便利，目前 GOTHIC 已有不少核能界的使用者。NAI 亦因 GOTHIC 程式發展成功，於 2011 年底被 Zachry 公司併購，成為 Zachry 公司的 Numerical Applications 部門。目前 NAI 仍在技術工作上維持獨立運作，人力規模約為 10 人左右。

圖二-2 Zachry 公司 Numerical Applications 部門

本所核工組於 2008 年引進 GOTHIC 分析程式，將其應用於國內核能電廠圍阻體熱水流分析，核一廠與核二廠的圍阻體分析專題報告分別於 99 年及 101 年通過原能會審查核備，相關分析技術亦有用於電廠中幅度功率提昇的安全評估工作。目前本所與台電公司正延續進行核三廠與龍門電廠圍阻體熱流分析技術之申照工作，為更深化技術能力，故與 Zachry 公司 NAI 部門進行技術合作，以增進國內對於圍阻體熱水流分析技術之掌握程度。本工作行程重點摘錄如下：

1. NAI 提供一間辦公室(該棟樓之 440 室)供本所相關人員使用，此次行程之主要接洽人為 Nate Carstens 博士，NAI 並提供有安裝 GOTHIC 程式的電腦，以便進行相關議題的說

明與討論。

圖二-3 NAI 提供給本所人員的辦公室

第 1 日(2013/07/09)首先由 Nate Carstens 博士簡介 GOTHIC 與其它程式進行平行耦合運算(Inter Process Communication, IPC)之能力，若兩個分析案例的計算區域(domain)之間有質量與能量交換，會相互影響，例如發生斷管事故(Loss of Coolant Accident, LOCA)時，有一分析案例模擬反應爐(Rector Pressure Vessel, RPV)，另一分析案例模擬圍阻體空間，RPV 內的冷卻水會流到圍阻體中，造成圍阻體升壓，而冷卻水沖放流量又受到圍阻體壓力之影響(事故後期)，RPV 與圍阻體之間會相互影響。如果想得到較實際(best-estimate)之模擬結果，兩分析案例應要平行執行耦合運算，藉由邊界條件回饋另一案例之變化狀況。

GOTHIC 程式之 IPC 功能除了能讓兩個以上的 GOTHIC 案例進行耦合運算，亦能與其它程式進行平行耦合運算。較常見的應用是將 RELAP5 建立之 RPV 模式與 GOTHIC 建立之圍阻體分析模式進行平行耦合運算，NAI 亦表示 GOTHIC 亦可與 RETRAN 進行平行耦合運算，RELAP5 與 RETRAN 程式皆為本所核工組常使用之分析程式。

Stan Claybrook 先生亦展示一 IPC 成功案例：核能電廠的緊急爐心冷卻系統(Emergency Core Cooling System, ECCS)管路如果出現氣體累積(gas accumulation)的狀況，為避免 ECCS 水泵因吸入過多氣體而導致損壞，需要評估氣體累積量與其存在時間長短。經說明，一般只要針對會有氣體累積的特定管路區域進行分析即可，無需過度耗時地將完整管路系統全納入考量，唯一例外是美國 Wolf Creek 電廠，該電廠過去曾發生 ECCS 管路氣體累積且會隨著管路四處移動，在無法確認氣體出現區域的狀況下，NAI

將所有 ECCS 管路系統全列入考慮，由於管路系統過於繁複，將其建立在一個 GOTHIC 模式中並不合適，因此 NAI 將其分為 5 個分析模式，藉由 IPC 來同時進行 5 個模式的平行耦合運算。

2. 第 2 日(2013/07/10)相關議題如下：

(1) RELAP (rev. 3.3)/GOTHIC simulation

要將 GOTHIC 與其它程式進行 IPC，必須要有該程式之原始碼(source code)，在其中加入讀取與寫出資料的指令，重新 compile 後才可執行 IPC。目前 NAI 已成功將 GOTHIC 與 RELAP5 (rev. 3.3) 進行 IPC 運算，其過程遠較 GOTHIC/GOTHIC 之間 IPC 設定過程繁複許多，且其程式碼的修改會依需依案例需求不同而改變(例如需要不同的輸入/輸出變數)，並非是一通用性之修改。

(2) Q&A responding

在本次公差出發前，核工組已將 GOTHIC 程式的相關提問寄送給 NAI，共有 11 項。與 NAI 現場討論時，再另增 1 項，NAI 提供之回應列於附錄(一)。

其中第 11 項是因核工組的嚴重事故相關業務要求與 AAC 公司合作，AAC 公司將反應器廠房洩漏量評估 GOTHIC 模式(7.1 版)提供給本組參考，由流體力學基本概念可知，洩漏量會與反應器廠房和外界壓差的平方根成正比，當壓差為負值，即外界環境壓力高於反應器廠房時，不應有洩漏出現。

由於 GOTHIC 7.1 是較早之版本，核工組將其轉換為 7.2 以後的版本，發現無法執行。經與 Nate Carstens 博士討論，7.1 版在計算負值之平方根時，會傳回一個無限大的數值(10^{32})，但不會停止計算，此一不合理之狀況已在 7.2 版之後修正，故 GOTHIC 7.2 之後的版本在遇到此狀況時都會停止計算，避免不合理的結果出現。而較新版本之 GOTHIC 可將控制變數(control variable)設定下限(例如 10^{-8})，可避免程式因此狀況而停止，以得到合理結果。本所核工組引進 GOTHIC 分析程式時已是 7.2 版，故目前核工組所有使用 GOTHIC 進行的分析工作均不受此問題影響。

第 12 項是現場與 NAI 人員討論時提出之疑問，因為 GOTHIC 程式在輸出氣體體積比率時有兩種選擇，一為 Gas volume fraction，另一則為 Gas volume fraction (dry)。經澄

清後，Gas volume fraction 為所有氣體的體積比例(包括水蒸汽)，Gas volume fraction (dry) 則是去除水蒸汽後，其餘氣體的體積比例。

(3) NAI 品保制度

為進一步瞭解 NAI 公司的品保制度，本所人員與品保經理 Kevin Wheelwright 進行品保意見交換，NAI 公司因承接核能安全相關計畫，常被 NUPEC 與其它電力公司進行稽查，該公司之品保制度除了符合美國核管法規 10CFR50 Appendix B 對於核能級品保之要求，並在去年修訂後加入 NQA-1 對於軟體品保之要求。由於與本所建立工作合約，NAI 亦有提供該公司的品質手冊作為參考。

GOTHIC 是由 EPRI 出資所發展的圍阻體分析程式，EPRI 每季皆會發佈程式的錯誤摘要報告(bug summary)，Bug summary 之範例如附錄(二)所示，會說明錯誤的狀況、分類等級以及其解決方法，供 GOTHIC 使用者參考評估，本所核工組相關人員亦會定期收到，並依核工組品保制度評估是否會影響現有成果或工作，且留下書面紀錄。在 NAI 公司內部，每個程式錯誤皆會成立其對應措施(Action Item)，並指定專門負責人，處理完成後會經由另外兩人審查其處理過程，通過後才結案公布。

NAI 亦將對應措施的處理過程電子化，Nate Carstens 博士以其處理的 Action Item AI8.0-205 作為展示，Action Item 負責人可在線上登錄進入資料庫，紀錄程式錯誤的狀況與其處理方式；審查人亦可在線上直接進行審查並撰寫建議，資料庫亦會紀錄對應措施的處理時間，不但對於無紙化有幫助，可避免人為誤植或紙本紀錄遺失等問題。

3. 第 3 日(2013/07/11)相關議題如下：

(1) Questions answered by Dr. Tom George

除了先前的提問以外，NAI 負責人 Tom George 博士另針對本所人員當場提問進行回應，摘要如下：

(A)目前美國 NRC 並沒有強制要求 GOTHIC 要與其他程式進行 IPC，目前所進行之 IPC 工作皆是配合顧客要求。另外，當初與 RETRAN 進行 IPC 之目的純粹展示 GOTHIC 程式的能力，因為兩者皆是屬於 EPRI 的程式。

(B) 當 GOTHIC 發現壓力大於 3000 psia，程式會自動停止運算，此項程式限制是因

為超過水的臨界壓力後，計算所需的流體性質會很不穩定，影響到數值穩定度。

(C) 在 GOTHIC 的輸出參數中，接節(flow path)的流量有 Continuous flow rate 與 Momentum flow rate 兩種，其差異主要是在密度的決定方式。Continuous flow rate 是採用上游體積的密度，Momentum flow 則是上下游體積的平均密度。經說明，Momentum flow rate 是在計算動量守恆方程式時所使用，求解動量方程式得到接節的速度之後，再用速度來求解質量與能量方程式。基於質量守恆的概念，在輸出接節的流量時，應選用 Continuous flow rate。

(D) 目前 GOTHIC 並沒有得到美國 NRC 的通用性核准(generical approval)，因該程式的應用範圍大，多數案例是電力公司向 NRC 進行個案申請(case-by-case)。目前比較接近通用性核准的案例，是西屋(Westinghouse)公司採用 GOTHIC 來進行該公司的 AP1000 圍阻體分析。

(2) PAR (Passive Autocatalytic Recombiner)

在福島事故之後，圍阻體與反應器廠房的氫氣處理方式受到重視。許多 PWR 乾式圍阻體在內部裝設被動式結晶再結合器(Passive Autocatalytic Recombiner, PAR)，PAR 不像一般的氫氧再結合器需要外接動力源，在喪失外部電源的情況下，PAR 依然能發揮功效，藉由化學作用減少氫氣的比例，降低氫爆發生的可能性。目前已有核能廠家生產 PAR，例如 AREVA 與 Westinghouse 公司，其產品外觀如下圖所示。

from AREVA web site

from Westinghouse web site

圖二-4 AREVA 與 Westinghouse 公司生產的 PAR

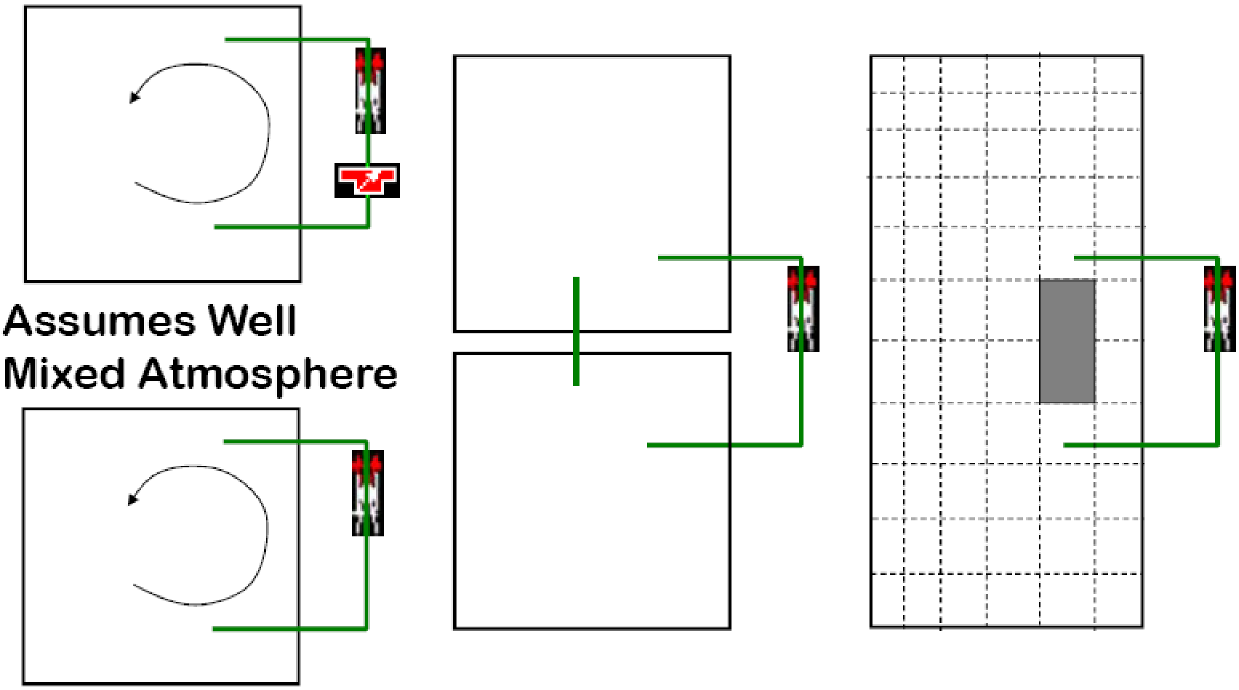
在 PAR 的熱流分析有數個因素需考量：複雜的空間幾何、模擬燃燒的尺度、氫氣/水蒸汽/空氣的局部分布、紊流效應、浮力效應、圍阻體中的系統作用、氫氣在事故時的產生率、PAR 的模式等因素。目前 PAR 的熱流模擬有三種方式：

(A)直接利用嚴重事故的分析程式來計算氫氣產生量以及分佈情形，例如本所核工組亦有的 MAAP 程式；

(B)先利用嚴重事故分析程式來計算氫氣產生量，再利用 GOTHIC 或 CFD 程式來計算氫氣三維分佈狀況；

(C)先利用嚴重事故的分析程式來計算氫氣產生量，再利用 GOTHIC 來計算氫氣分佈狀況，最後使用 CFD 評估局部空間的氫氣分佈狀況。

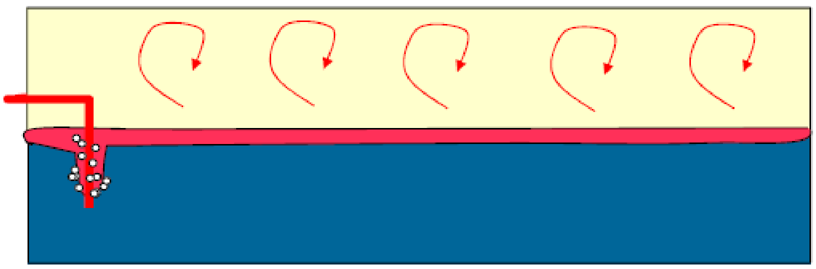
GOTHIC 程式可採用程式內建的 Recombiner 模組建立 PAR 的模式，PAR 本身的氫氣再結合效能，需由廠家提供實驗數據或產品規格等參數，將其作為 GOTHIC 程式中 Recombiner 模組所需之輸入參數。Recombiner 需設置在接節上，如果空間混合程度較好，可直接使用一個積總體積(lumped volume)模擬空間即可，如下圖左所示；若要呈現氣體進出 PAR 的差異，可採用下圖中的方式，將進出 PAR 的兩空間分開；若需得知較詳細的氫氣分佈狀況，需使用 GOTHIC 程式的次體積(sub-divided volume)切割功能，將一個大空間切割成數個體積模擬，並用 GOTHIC 的障礙物(blockage)功能處理 PAR 佔據的空間，如下圖右所示。



圖二-5 GOTHIC 程式模擬 PAR 作用方式之示意圖

(3) Fukushima suppression pool behavior

福島事故發生後，圍阻體抑壓池溫度層化(stratification)亦是受關注的現象之一，以往 BWR 圍阻體分析常使用單一節點來模擬抑壓池，該方式假設抑壓池水混合良好，故無法顯示池水溫度層化現象。然而福島三號機量測到的圍阻體壓力明顯高於分析預測值，因此推測，爐心隔離冷卻(Reactor Core Isolation Cooling, RCIC)系統中推動水泵的汽機在長時間運作下，持續將蒸汽排放到抑壓池中，蒸汽被排放到池水後會往上流動，若沒有將蒸汽完全冷凝，蒸汽往上流至濕井空間後會造成直接加壓，而且池水溫度出現層化現象，上層的溫度較下層高，如下圖所示。



圖二-6 RCIC 汽機排蒸汽造成抑壓池溫度層化之示意圖

為模擬此現象，NAI 建議：(a)至少要二維模式模擬濕井；(b)重力方向的節點數目要

足夠；(c)選用 Bounded Second Order Upwind 數值離散方式；(d)使用 Conjugate Gradient 求解壓力(特別是節點數目超過 1000 個的案例)。

NAI 選擇與兩實驗案例進行比對，一為 GE 公司的 Monticello SRV Test，測試 Mark I 型圍阻體在承受安全釋壓閥(SRV)開啟造成的蒸汽沖放；另一則是芬蘭 Lappeenrenta 大學的 POOLEX Test，該測試藉由垂直管將蒸汽注入一開放的水槽中。GOTHIC 與此二測試的結果皆有良好吻合，相關說明可參照附錄(三)。

(4) Water/Pressure surge (annulus pressurization)

電廠中有管路是用於將蒸汽導入液態水中冷凝，例如 SRV、HPCI 或 RCIC 汽機的排汽管路，管路內部蒸汽被冷凝後，壓力會明顯下降，若壓力過低，液態水可能會被吸入管路中，造成水槌(water hammer)現象，可能損壞管路結構。GOTHIC 亦可用於模擬管路中的水槌現象，且與 Delft Hydraulics 實驗室及 EPRI 的測試比對結果相吻合，如附錄(四)所示。

此外，GOTHIC 亦可用於 BWR 圍阻體的環狀區加壓負荷(Annulus Pressurization Load, AP Load)之計算，環狀區係 BWR 反應爐與生物屏蔽牆之間的空間，由於環狀區內有高能管路經過，例如飼水管或再循環管路，若發生斷管，需計算環狀區內的壓力變化，進而評估生物屏蔽牆是否能承受此負荷。NAI 展示 Mark II 圍阻體 AP Load 分析案例，環狀區內分為 20x20 個二維節點，各穿越管路佔去的空間亦有列入考慮，藉此計算發生斷管時的壓力暫態變化，相關資料如附錄(四)所示。

4. 第 4 日(2013/07/12)相關議題如下：

(1) PWR Long-term M&E release

我國核三廠一二號機皆為 Westinghouse 公司的 3-loop PWR，其電廠終期安全分析報告(FSAR)第 6.2 節中，圍阻體分析使用之初始爐心熱功率為 102%額定原始熱功率，目前核三廠已執行過小幅度功率提昇，如果要再進一步提昇功率，圍阻體分析勢必要重新進行。NAI 曾針對 PWR 圍阻體 GOTHIC 分析模式撰寫一份指引(guideline)，且已被美國 NRC 核准，其中包括 PWR 長程沖放質能條件(long-term mass and energy release)之計算模

式亦有說明，由於與本所進行合作，該份指引內容已提供給本所核工組參考。

依據 Stan Claybrook 先生說明，PWR 圍阻體分析的短程沖放質能條件(由 blowdown 至 reflood 期間)仍由原廠家所提供，以邊界條件提供給圍阻體分析模式進行計算。但在 reflood 期間之後，則是直接由 GOTHIC 建立一次側(primary side)與二次側(secondary side)的系統，由其計算長程沖放條件。為避免短程與長程沖放條件的不連續，一次側與二次側系統的初始狀態需與廠家提供資料一致，且要避免 GOTHIC 一次側與二次側系統內的熱導體在開始沖放前就與流體進行熱交換。

(2) Neutron Kinetic

Tom George 博士表示 GOTHIC 是從 COBRA 程式逐漸發展而來的，與圍阻體分析無關的功能模組在發展過程中被移除掉。然而近幾年 NAI 進行 NuScale 反應器相關之技術研究，NuScale 公司希望能使用單一程式模擬相關的熱流現象，因此 NAI 重新撰寫計算中子通量變化的 point kinetic 模式，主要由 Donald Todd 博士(已離開 NAI)與 Nate Carstens 博士負責相關工作，該功能預定將加入 GOTHIC 8.1 版中。

(3) Spent Fuel Pool

在福島事故發生前，NAI 曾接受西班牙 Centrales Nucleares Almaraz-Trillo 公司(CNAT)委託進行用過燃料池(spent fuel pool, SFP)的研究，當時主要由 Donald Todd 博士負責，原本 CNAT 的目的是要評估是否能挪移池中的用過燃料，有效利用池內空間。然而在福島事故發生後，其工作方向便轉變為探討用過燃料池的安全。

NAI 的 SFP 分析模式可分為三個層次：(1)全池模式；(2)多燃料束模式以及(3)單一燃料束模式。全池模式是將整個 SFP 分割為數個三維節點，可顯示自然對流效應，用於計算池內的溫度、水位與流場變化。多燃料束模式則是 4x4 燃料束的分析模式，燃料束在水平方向只用一個節點，在垂直方向的節點數目則在 20 個以上，並有加入鋯水反應的放熱效果(此為 NAI 特別為執行 SFP 分析所建立之功能，尚未加入於現有之 GOTHIC 程式版本中)，可計算局部溫度變化，並探討不同排列方式造成的影響。單一燃料束模式僅用於與實驗量測值比對，確認其可信度。

用過燃料池的噴灑作用，則是在全池模式上方再增加一個積總體積(lumped volume)，該積總體積連接至一個代表噴灑流量的邊界條件，再藉由 GOTHIC 程式的

3D-connector 連接至用過燃料池最上方的節點，並在 3D-connector 放置一噴嘴，將進入用過燃料池上方的流量全轉化成液滴，來模擬噴灑的效果。

Mark Lanza 先生亦展示 SFP 遇到地震的水位變化模擬結果，在 GOTHIC 模式中，將 SFP 一側體積內的孔隙度(porosity)設為一個時變函數，池水因側邊空間受到擠壓，便造成水面波動，藉此技巧模擬地震的強度與頻率，分析其對 SFP 之影響。

(4) Fukushima Reactor Building hydrogen distribution and venting

福島事故最令一般民眾印象深刻的一幕，即是反應器廠房發生氫爆，因此核能界在福島事故後，開始重視反應器廠房在發生嚴重事故後的氫氣濃度分布。NAI 針對福島第一電廠一號機的反應器廠房空間建立 GOTHIC 三維分析模式，包括內部主要結構等皆有考量，如附錄(三)所示。

在此分析模式中，反應爐與一次圍阻體的狀況是由 MAAP 程式分析，以提供氫氣產生量作為 GOTHIC 分析的邊界條件。並針對四個洩漏途徑不同之案例進行探討：(1)乾井頂部 flange 洩漏；(2)乾井頂部 flange 洩漏且 Wetwell venting 有開啟；(3)乾井頂部 flange 洩漏且備有氣體處理系統(Stnadby Gas Treatment System, SGTS)的連通閥(tie valve)失效；(4)只由反應器廠房一樓洩漏。假設事故發生時，反應爐內因鋯水反應產生的氫氣會先排到一次圍阻體中，再洩漏至反應器廠房空間。分析結果顯示，只要乾井頂部 flange 洩漏，反應器廠房頂部的氫氣濃度就會超過可燃限值，且若洩漏位置在反應器廠房低處，氫氣在廠房空間的分布會較均勻。此部分 NAI 純粹進行反應器廠房空間氫氣濃度分布的研究分析，並沒有探討後續的處理應變方式，而國內電廠除了原有的氫氧再結合器，亦考慮再另安裝 PAR，可有效避免氫氣濃度過高的安全疑慮。

(5) Gas transport in ECCS piping

如果 ECCS 管路中有空氣累積，當水泵開始運作，過多氣泡進入水泵可能會導致其損壞，此亦是美國 NRC 發佈 GL 08-01 之目的。NAI 亦承接過相關案例，因為氣體在管路中的傳輸現象是分析的重點，因此建立 GOTHIC 模式時，管路不可簡化使用 flow path 代替(因 GOTHIC 不考慮 flow path 的質量守恆)，必須要分割為控制體積，且至少使用二維節點來模擬管路部分。管路模式之建立需要參照電廠的大量 P&ID 圖面，每條管路的水平與垂直部分都要考慮，因此建立此種模式會需消耗相當的人力工時。

Stan Claybrook 先生表示，相關案例通常只要針對有發現氣泡出現的特定區域分析即可，僅有 Wolf Creek 電廠因不能有效確認受到影響的管路區域，只好將所有 ECCS 管路全部列入 GOTHIC 模式中，NAI 投入了 3 位工程師，花了約 8 個月時間才建立該廠的詳細管路模式。且因模式需要將管路細分為控制體積來模擬，該廠的 ECCS 管路分析模式包含了太多的控制體積，不適合全部涵蓋在單一 GOTHIC 案例中，因此將各管路系統分別建立其所屬的 GOTHIC 案例，該廠的 ECCS 管路系統總共建立了 5 個 GOTHIC 案例檔，再使用 IPC 功能進行運算，將各案例之間的質量、動量與能量交換進行連結。

5. 與 NAI 未來可能之合作項目

本次因計畫工作而參訪 Zachry 公司 NAI 部門，進行相關經驗交流，由於 NAI 是 GOTHIC 程式的發展者，且有豐富之實際應用經驗，此行受益良多。由於 GOTHIC 程式還有許多實際用途，有助於國內電廠進行評估或改善工作，未來本所核工組 GOTHIC 工作人員有下列相關工作要進行，可能有機會與 NAI 再進行交流合作：

(1) PAR：國內核電廠考慮其圍阻體內安裝 PAR，會需要 GOTHIC 計算事故時的氫氣濃度分布。

(2) ECCS 管路氣體累積：GOTHIC 可用於評估 ECCS 管路氣體狀況的嚴重程度。

(3)用過燃料池：分析用過燃料池在喪失冷卻水後的熱流分析。

(4)環狀區增壓負荷(AP load)：此為 BWR 圍阻體次隔間(subcompartment)分析中的重要項目。

進一步與 NAI 人員討論後，明年較有可能合作之工作項目為 PAR 與 AP load 兩項，本所人員與 NAI 討論而提出之後續合作內容如附錄(五)所示。

(三) AREVA 公司 RLA 審查工作

核二廠現正執行中幅度功率提昇，二號機將在週期 23 期中(Middle of cycle, MOC)進行切換，而核二廠現行燃料廠家為 AREVA NP 公司，燃料再填換分析(Reload Licensing Analysis, RLA)工作由該公司負責執行，Rev.0 報告須於 7 月 31 日前完成，預計於今年 8 月將完稿陳送原能會審查。

本次公差第二個目的，即是赴 AREVA 公司(同樣位於里奇蘭市)進行核二廠二號機週期

23 RLA 審查工作，以配合陳送原能會審查之規畫。此外，將與 AREVA 討論核二廠爐心佈局設計優化技術，以增進本所技術能力。

AREVA 提供 858 與 865 兩間辦公室，並提供 4 臺連接至該公司資料庫的電腦供本所人員使用，本所人員可藉由電腦連線查閱本次 RLA 相關資料，包括 AREVA 不對外公開的手冊、計算書等資料，然因該公司對於資料保護的要求，不提供紙本翻閱，僅能藉由該公司提供之電腦閱讀文件的電子檔。

1. 第一日(2013/07/15)相關議題如下：

與 AREVA 公司相關人員開會討論此次 KS2C23 中幅度功率提昇 RLA 審查的進行方式，AREVA 公司與會人員 Kris Mitchell (manager), Robert Follette (manager), Sean Mellinger (superviser), Dang Patchana (superviser)及 Stone Luo (engineer)等人。會中雙方同意與 7 月 23 日舉行一次審查會議，每日下午 2:30 與 Sean Mellinger 討論安全分析方面的審查意見，中子分析方面的問題則隨時可以找 Dang Patchana 討論。台電公司所提出的審查意見已由 AREVA 公司回覆，相關內容如附錄(六)。

此次 AREVA 提供審閱的 KS2C23 SPU 相關計算書如下表：

Notebook	Description
FS1-0009995, Rev 1	Kuosheng Unit 2 Cycle 23 Fuel Cycle Design for Stretch Power Uprate (SPU) Program
FS1-0010187, Rev 1	Kuosheng Multicycle Step-Through to Support SPU Generic Licensing Analyses
FS1-0010617, Rev 1	Kuosheng Cycle Independent Loss of Feedwater Heating Analysis for SPU
FS1-0010619, Rev 1	Kuosheng Unit 2 Cycle 23 Control Rod Drop Accident Analysis for SPU
FS1-0010620, Rev 1	Kuosheng Unit 2 Cycle 23 Stability Analysis for SPU
FS1-0010921, Rev 1	Kuosheng Cycle Independent Mislocation Analysis for SPU
FS1-0010975, Rev 1	Kuosheng Cycle Independent Flow Runup and $LHGRFAC_f$ Analysis for SPU
32-9197028-000	KS2C23 SPU Disposition of Events
32-9197029-000	KS2C23 SPU Heat Balance Analysis
32-9197030-000	KS2C23 SPU Pellet to Cladding Heat Transfer Coefficient
32-9197031-000	KS2C23 SPU Transient Inputs

32-9197032-000	KS2C23 SPU Turbine Trip Without Bypass Analysis
32-9197033-000	KS2C23 SPU Load Reject Without Bypass Analysis
32-9197034-000	KS2C23 SPU Feed Water Controller Failure Without Bypass
32-9197035-000	KS2C23 SPU ASME Over-Pressurization
32-9197036-000	KS2C23 SPU LOCA Limiting Power History Analysis
32-9197037-000	KS2C23 SPU $MCPR_f$ Analysis
32-9197038-000	KS2C23 SPU MCPR Safety Limit Analysis
32-9197039-000	KS2C23 SPU Thermal Limits
32-9197190-000	KS2C23 SPU Thermal Data for Mechanical Design

2. 第二日(2013/07/16)相關議題如下：

(1)AREVA 目前送審中的 ACE correlation，除了 K-factor 的計算方法有改變外，additive constants 是否也有變動？

Sean 表示，就他所知，additive constants 好像沒有變動，不過他也不是很確定，將再詢問 ACE correlation 的專家後，再提供確定的答案。

(2)已核准的 ACE correlation 與送審中的 ACE correlation 在 K-factor 計算方法上的不同，對於 operability assessment 中穩態 MCPR 計算結果的差異，是否能加以說明？

Sean 表示，此問題涉及 ACE correlation 的理論，他個人無法做完整的回答，將另外安排 ACE correlation 方面的專家，找時間另外討論。

(3)目前送審中的 ACE correlation 專題報告，NRC 審查的進度如何？預計何時可以取得 SER？

Sean 表示，他個人預計今年秋天可以取得 NRC 的 SER 草案，今年底可能可以取得 NRC 正式的許可。

(4) AREVA 公司的水位計算結果與 INER 使用 RETRAN 計算的結果有出入，是否可提供相關之資料予以參考？

Sean 表示，兩方使用的程式不同，結果亦會有不同。可提供 COTRANSA2 User’s Manual 以供參考。

3. 第三日(2013/07/17)相關議題如下：

(1)關於昨日所問ACE correlation送審中版本的additive constants是否有變動的問題，Sean Mellinger表示，經過詢問ACE correlation方面的專家，確認送審中的ACE correlation其additive constants確實有所變動。另外，明天下午將安排ACE correlation方面的專家討論與答覆相關的問題。

(2)Operability assessment報告中對於額定功率與非額定功率狀態下的MCPR分別使用已核准與送審中的ACE correlation版本分別加以計算，並比較量化其差異。結果顯示，有些狀態點兩中版本的計算結果差異不大，但有些狀態點兩種版本的計算結果差異很大，請問其原因為何？

Dang表示，主要的原因時兩種版本的K-factor計算的方法不同所造成，差異的程度與軸向功率分布、變態沸騰(boiling transition)發生的位置及軸向各節點的節點K-factor (nodal K-factor)的大小有關。舉例來說，若燃料上半部的節點K-factor較大（假設為1.7），而燃料下半部的節點K-factor較小（假設為1.2），在軸向功率分布為偏向底部(bottom-skewed)的情形下，發生變態沸騰的軸向位置將偏向燃料下半部。在這種情形下，利用已核准的ACE correlation方法所得到的臨界熱功率較小，CPR會較小，而使用送審中的ACE correlation版本所得到的臨界熱功率較大，CPR會較大。因此，每個燃耗點兩種版本的分析結果差異都有所不同，差異的大小視個案而定。

(3) 控制棒誤抽事件的分析結果顯示，已核准版本的ACE correlation與送審中版本的ΔCPR計算結果有差異，其原因為何？

Dang表示，兩種ACE correlation版本在K-factor的計算有本質上的差異，送審中的版本不會使用到發生變態沸騰的軸向位置下游節點的K-factor數據，依照其經驗，當變態沸騰在軸向上發生的位置較偏向燃料束下半部時，將會造成較大的計算結果差異。

(4) 根據核二廠二號機週期二十三的RLA報告，新燃料A10-4046B-14GV75的數量為59束，A10-4041B-15GV75的數量為111束。通常新燃料的數量為偶數，為何這個週期的新燃料數量為奇數？

Dang表示，這兩批次的新燃料在運送到台灣進行燃料檢查時發現各有一束燃料的spacer損壞，致使這兩批新燃料的數量由偶數變成奇數。

4. 第四日(2013/07/18)相關議題如下：

早上 Dang Patchana 安排 AREVA 公司機械分析方面的專家 Ali Zbib 簡報，並討論 Zr-4 燃料匣彎曲方面相關的問題。

(1)AREVA 目前正在發展 Zr-4 的燃料匣彎曲預測模式，目前正持續地在一些美國電廠蒐集 Zr-4 燃料匣彎曲的數據，就前蒐集到的 Zr-4 燃料匣彎曲的數據來看，Zr-4 的彎曲程度明顯的較 Zr-2 的彎曲小。

(2)AREVA 目前發展中的燃料匣彎曲的預測模式，同時考慮了中子通量梯度(flux gradient)所造成的燃料匣彎曲及 shadow corrosion 所造成的燃料匣彎曲，可用以取代目前所使用的 SIL320 燃料管理導則(fuel management guideline)以及與 shadow corrosion 相關的燃料管理導則(例如 EFID)。

(3)以目前量測到的 Zr-4 燃料匣彎曲的數據來看，其彎曲程度應該是不會造成控制棒插入時有摩擦力過大的情形。

下午 Sean Mellinger 安排 ACE correlation 方面的專家針對送審中與已核准版本的差異做一簡單的說明並答覆相關問題。

(1)是否會發生變態沸騰受 Entrainment、Deposition 及 Evaporation 三個因素的影響，其中 Evaporation 這一項與 K-factor 有關，K-factor 越大，水的蒸發越多，越容易發生變態沸騰。在發生變態沸騰之前燃料棒表面仍有一層水膜覆蓋，此水膜的厚薄與流體上游的蒸發情形有關，也就是說與燃料棒上游節點的 K-factor 有關，上游節點的 K-factor 對於所觀察的節點是否會發生變態沸騰會有影響，而下游節點的蒸發情形或 K-factor 則不應對於所觀察節點是否發生變態沸騰有所影響。

(2)已核准版本的 ACE correlation 於計算中所用的 K-factor 係採用軸向體積平均而得，因此在變態沸騰發生位置下游節點的 K-factor 會影響臨界功率(critical power)的計算結果。

(3)AREVA 在送審中的 ACE correlation 版本提出兩種 K-factor 的計算方式，一種 rod-by-rod K-factor，另一種是 max-rod K-factor。若使用 rod-by-rod K-factor，則燃料束中的每一根燃料棒都要計算其臨界功率，然後取其中最保守者。若使用 max-rod K-factor，則在計算臨界功率時只取每一個節點中最大的 K-factor。就計算時間而言，若使用 rod-by-rod K-factor，CPR 的計算會相當耗時，對於爐心監測系統(core monitoring system)是一大考驗，目前 AREVA 公司

已針對 rod-by-rod K-factor CPR 的計算發展出快速的計算方法，已可滿足爐心監測系統即時計算 MCPR 的需求。就計算的保守性而言，使用 max-rod K-factor 的 CPR 計算結果會較為保守，目前這種方法只有 Brunswick 電廠在使用。

5. 第五日(2013/07/19)相關議題如下：

(1) 針對核二廠中幅度功率提昇的相關分析需求，AREVA 完成了核二廠一號機與二號機的多週期設計報告，以做為下游慢速暫態通用性分析(generic analysis)結果的可適用性評估的基礎，亦做為 ACE correlation K-factor 計算方法修訂後中幅度功率提升的可運轉性評估(operability assessment)的基礎。在飼水加熱喪失通用性分析結果的可適用性評估計算書中，AREVA 針對多個週期的週期初到週期末的燃耗點使用 MICROBURN-B2 進行飼水加熱喪失事件分析的 FMCPR 計算，並將此計算結果與通用性分析關係式的預測結果比較，檢視通用性分析結果關係式預測的 FMCPR 是否仍較為保守。在 KS1C25 的分析結果發現，在燃耗點 7.92 GWd/MTU 時，通用性分析關係式的預測結果不夠保守。為了證明通用性分析關係式仍然可以適用，AREVA 調整了此燃耗點的控制棒佈局，使其 IMCPR 更接近 OLMCPR，然後以此調整後的控制棒佈局重新計算飼水加熱喪失事件後的 FMCPR，結果顯示此 FMCPR 可為通用性分析關係式涵蓋。

對於其它使 IMCPR 接近 OLMCPR 的控制棒佈局是否亦可以得到類似的結果，Dang Patchana 表示，在 KS1C16 的飼水加熱喪失事件分析亦做過類似的分析，結果亦顯示當 IMCPR 接近 OLMCPR 時，經由程式分析所得的 FMCPR 可為通用性分析關係式所涵蓋。

6. 第六日(2013/07/22)相關議題如下：

(1)由於目前 KS2C23 的爐心中已經沒有 Zr-2 的燃料匣，但在 RLA 報告的 4.2.5 節仍然有減輕 Zr-2 燃料匣彎曲的燃料管理導則(fuel management guideline)， 與 Dang Patchana 討論後，Dang Patchana 表示將再與台電人員進一步溝通。

7. 第七日(2013/07/23)相關議題如下：

(1)目前送審中的 ACE correlation 版本，對於 K-factor 的計算方式有兩種，是否 NRC 對此兩種 K-factor 的計算方式都會同意？由於目前核一、二廠的 operability assessment 使用的是 rod-by-rod 的 K-factor 計算方式，若 NRC 只同意 max-rod K-factor 的計算方式，對於核一、二廠的影響為何？

Sean Mellinger 表示，目前不清楚 NRC 是否兩種 K-factor 的計算方式都會同意。若使用 max-rod K-factor，他個人預期不會造成爐心佈局設計上的困難，OLMCPR 的變動可能會小於 0.01，爐心新燃料束需求的數量應該不會因此而增加。

8. 第八日(2013/07/24)相關議題如下：

(1) 依據控制棒誤抽通用性分析結果的可適用性評估計算書，在 100%額定功率下的 $\Delta MCPR_{95/95}$ 大於通用性分析的結果，AREVA 為了證明通用性分析結果仍然可以適用，調整了某些燃耗點的控制棒佈局，使其 IMCPR 更接近 OLMCPR。控制棒佈局調整後，爐心流量需做相對應的調整，但其條件為維持爐心流量在 80%以上。而在飼水加熱喪失通用性分析結果的可適用性評估計算書中，為了證明通用性分析關係式仍然可以適用，AREVA 調整了 KS1C25 在 7.92 GWd/MTU 時的控制棒佈局，使其 IMCPR 更接近 OLMCPR，而為了確保初始狀態的合理性，爐心流量需維持在 88%以上。對於這兩個分析在爐心流量的使用上不一致的情形，Dang Patchana 認為，只要爐心流量在 flow window 範圍內即屬合理，故沒有一致性的問題。

(2)燃料束錯置事件的分析需考慮全週期 MCPR 最大的燃料，然後將高反應度的燃料束錯置到該束燃料的鄰近位置以分析ΔMCPR。檢視中幅度功率提昇的燃料束錯置分析計算書發現，KS2C25 的全週期 MCPR 最大值出現在 10.56 GWd/MTU，但該燃耗點並未被選擇做為燃料束錯置分析的燃耗點。

針對此項問題，Dang Patchana 表示，由於 10.12 GWd/MTU 與 10.56 GWd/MTU 的 MCPR 出現在同一燃料束，而 10.12 GWd/MTU 已被選擇做為燃料束錯置分析的燃耗點之一，且燃料束錯置之後整個爐心燃耗計算會從週期初到週期末重新計算一次，並從所有的燃耗點中找出全週期最大的ΔMCPR，因此在計算書中並未看到在 10.56 GWd/MTU 的燃料束錯置分析。

9. 第 9 日(2013/07/25)相關議題如下：

(1)在暫態安全分析中，急停控制棒插入反應度(scram reactivity)會影響暫態的分析結果。AREVA 的暫態安全分析使用 COTRANSA2 程式，其所需的一維急停控制棒插入反應度的資訊來自於 MICROBURN-B2 從全棒出(all rods out)到全棒入(all rods in)的計算，但 MICROBURN-B2 從全棒出到全棒入的計算，從棒位 48 到棒位 24 每隔 2 節做一次計算，接下來就直接插到棒位 0 做計算，從棒位 24 到棒位 0 的中間並未做任何的計算，而從棒位 24 到棒位 0 中間的急停控制棒反應度則由 COTRANSA2 做內插而得。由於暫態安全分析時，為了得到保守的分析結果，通常使用一偏向爐心頂部的軸向功率分佈，就急停控制棒插入反應度而言，從棒位 24 插入到棒位 0 會提供較多的負反應度，反而在此棒位區間 MICROBURN-B2 要做較詳細的計算，才能提供 COTRANSA2 在此棒位區間詳細正確的急停控制棒插入反應度。

關於此項疑問，Sean Mellinger 表示，早期的 MICROBURN-B 程式在進行從棒位 24 逐漸插入到棒位 0 的計算時會有收斂的問題，而由於暫態分析最大的ΔMCPR 通常出現在控制棒插入到棒位 24 之前，因此才會有目前的這種計算方式。雖然目前的 MICROBURN-B2 程式可能不會有收斂的問題，但因為從棒位 24 到棒位 0 較詳細的控制棒插入計算對於目前的暫態分析沒有任何好處，因此並未考慮改變目前的計算方式。

10. SPU RLA 及 Operability 報告值得注意的項目討論

(1) 核二廠二號機週期 23 SPU 後功率由現行之 2943 MWt 提昇至 3001MWt ，對 RLA 而言主要的影響為使用更新後之汽機控制閥特性曲線，該曲線是基於最近週期的運轉資料外插至 SPU 的功率，使得汽機控制閥的初始閥位較高，此影響 Load Rejection with No Bypass 之暫態分析結果，雖然此暫態在 RLA 中不是 Limiting case，但值得注意此種改變。

(2) K-factor modification 對 AOO OLMCPR 主要的影響為 MCPR safety limit 的降低使得 OLMCPR 降低，而非 ΔCPR 的降低，實際上 K-factor modification 前後之 AOO ΔCPR 並無明顯不同，主要為 K-factor modification 使得"ratio of predicted to actual rods in boiling transition"這個參數明顯增加以致 MCPR safety limit 明顯降低。此在 Operability 報告中未討論，值得注意。

(3) Pressure Regulator Downscale Failure 於 SPU RLA 中重新分析，證明仍符合 Infrequent Event 劑量接受準則，在分析中引入了 AOO 之 MCPR safety limit 概念，因為劑量分析決定於爐心中有多少燃料棒損壞，而 MCPR Safety Limit 程式 SAFLIM2 可提供在選定 MACPR Safety Limit 下，爐心中有多少燃料棒達到 Boiling transition 而損壞，因此間接證明 Pressure

Regulator Downscale Failure 符合劑量接受準則的方法為先訂定劑量限值對應之破損燃料數及對應之 MCPR Safety Limit($MCPR_{PRDF}$)，然後假設在 AOO 之 MCPRp 運轉下，計算 Pressure Regulator Downscale Failure 之 ΔCPR，得到暫態之最小 MCPR 並與 $MCPR_{PRDF}$ 比較，若大於 $MCPR_{PRDF}$ 則符合接受準則。

核二廠二號機週期 23 SPU RLA 審查意見涉及中子分析、熱水力分析、安全分析與機械分析等領域，並涵蓋 Operability Report 之評估，經事先之澄清與討論後，最後彙整有 33 項須由 AREVA 公司正式答覆，審查意見及 AREVA 公司之答覆已整理交付台電公司。

三、心　得

(一)赴 NAI 進行圍阻體分析相關工作：

本所核工組近年來引進 GOTHIC 程式，並開始應用在國內核電廠圍阻體安全分析工作。今年與 NAI 正式進行合作，NAI 為 GOTHIC 程式發展者，對於程式能力與限制等熟知甚詳，另一方面 NAI 因常接受美國電力公司委託工作，協助核電廠通過美國核能管制委員會(NRC)對於相關安全議題審查，亦有參與新型反應器(Nu Scale)的安全分析工作，對於福島事故後的分析工作，NAI 亦有與國際間相關組織合作的經驗。

本所相關人員與 NAI 交流，收穫甚豐，除了增進 GOTHIC 技術的瞭解外，本次行程另有兩項心得：

1.核能級品保之要求：本所目前已有全所性的 ISO 9001 品保要求，而所內各功能組亦依其特別需要，製定自行的核能級品保制度，以符合 10CFR50 Appendix B 核能級品保要求，例如核工組與核儀組等功能組，而近年來台電公司委託本所執行之計畫，亦多要求具備核能級品保。NAI 成立已久，且是以研究發展與技術服務為主的公司，性質與本所核工組較為接近，且 NAI 常被 NUPEC 及電力公司進行稽查，其品保制度具有參考價值。

2.較新之核能安全議題：NAI 會直接與美國的電力公司及核管單位接觸，參與較新核能安全議題的機會較高，例如 PAR 或 GL 08-01 等議題，台灣的核電廠尚無經驗或未開始著手進行，藉由與 NAI 的合作經驗，可得知美國對於相關議題的處理方式，此亦是一收穫。

(二)赴 AREVA 進行 RLA 審查工作：

1.此次赴 AREVA 訪問，除了進行 RLA 的審查工作外，亦藉此機會瞭解廠家的慢速暫態分析技術發展，做為將來本所發展相關分析方法的參考。此次訪問發現，AREVA 的燃料束誤旋轉分析方法已經有所改變。該公司以往的燃料束誤旋轉分析方法係利用 CASMO-4 的色組(colorset)分析模式以模擬燃料晶格在誤旋轉後 water gap 的變動，計算誤旋轉後的晶格功率與局部功率峰值，進而分析出誤旋轉後的 MCPR。由於 CPR 的計算與軸向功率分佈有關，必須考慮燃料棒軸向功率的累積效應，而爐心燃料佈局對於事件的分析結果也會有影響，以 CASMO-4 的二維晶格計算方式並無法正確地模擬這些效應，要較正確地模擬這

些效應，就必須進行燃料束誤旋轉後的三維爐心計算。

2.爐心燃料佈局設計優化技術在佈局設計自動化的領域一直是一項被關注的研究議題，本所使用基因演算法(genetic algorithm)建立爐心燃料佈局設計的優化技術及控制棒佈局設計的優化技術，目前已有初步的成果，但在接近週期末兩個棒序中間的燃耗點有時會有搜尋不到符合熱限值設計條件的控制棒佈局的情形，經研究並與 AREVA 具有多年爐心佈局設計經驗的工程師 Dang Patchana 討論後，覺得有一些研究方向可以一試。

(1)在週期末兩個棒序中間的燃耗點在調整控制棒佈局時常有抽棒的需要，若該控制棒附近的燃料束是屬於功率較高的燃料束，在抽棒後常會出現 MCPR 餘裕不足的情形。依照基因演算法的適應函數(fitness function)設計，在每個棒序的起始燃耗點熱限值表現最佳的控制棒佈局會被選擇做為此棒序往下燃耗的控制棒佈局，而熱限值表現最好的控制棒佈局可能利用深棒過度抑制了高功率燃料束的功率故能得到較好的熱限值餘裕，但在接近週期末時，由於熱過剩反應度下降的很快，常有抽深棒以使爐心維持臨界的需要，但在抽深棒後，原先被抑制的高功率燃料束就可能造成 MCPR 的問題。因此，在基因演算法的適應函數中可以考慮加入一些與徑向功率分佈有關的部分，以避免被過度抑制的高功率燃料束在抽棒的過程中造成 MCPR 的問題。方法是先利用全棒出的爐心計算找出功率最高的一些燃料束，從基因演算法找出的一些符合設計要求的控制棒佈局中，利用一些方式檢視高功率燃料束的功率被該控制棒佈局抑制的程度，例如：與鄰近深棒的距離或這些燃料束在全棒出及有控制棒佈局下的功率差異。若高功率燃料束被抑制的程度過大，將來在抽棒時可能會有 MCPR 的問題，應避免選擇該控制棒佈局。

(2)上述方法是從棒序的起始燃耗點來考慮控制棒佈局的選擇，然高功率燃料束的形成有可能是該燃料束在前面被燃耗的太少，因此從週期初開始的每一個個燃耗點可能就需注意燃耗的平均性，尤其是新燃料束，原因是新燃料束因為含有 Gd，在其 Kinf 峰值燃耗點之前其反應度會隨著燃耗而增加。原則上，在較靠近爐心中間區域的新燃料束應使其 dominate zone 的燃耗值大於 Kinf 峰值燃耗點，以避免在週期末時因抽棒而造成熱限值的問題。因此，應避免靠近爐心中間區域的新燃料束燃耗過度不均的情形。方法是在適應函數中加入新燃料徑向功率分佈的考量，使所選擇的控制棒佈局能同時兼顧熱限值餘裕與新燃

料的平均燃耗。

(3)如果燃料的底部被燒得太少，在週期末抽棒時就容易有 MCPR 或 LHGR 餘裕不足的情形，要避免此問題，就必須注意控制棒佈局的 axial tilt，從週期初到週期中應儘量選擇軸向功率分佈較為偏向底部的控制棒佈局。不過，依照以往的經驗，若週期初到週期中的軸向功率分佈過度偏向底部，在週期末時也容易有 MCPR 餘裕不足的問題。因此，在適應函數中的 axial tilt (或 axial offset)目標值必須適度地偏向底部，不能過度地偏向底部，以避免在週期末時無法找到符合設計要求的控制棒佈局。

四、建　議　事　項

(一)本次公差純粹為技術工作，並非正式的品保稽核，然而本所近年來對於品保要求逐漸提高，不但有全所性的 ISO 9001 品保，有特別需要的功能組，例如核工組亦有組內的核能級品保制度，以符合 10 CFR 50 Appendix B 的核能級品保要求。本次公差目的地之一的 NAI 性質與本所核工組較為接近，且因與本所簽訂工作合約，可查閱其品質程序書等重要內部文件。若本所品保人員有機會進行交流或稽查工作，必會對國外核能級品保制度有更進一步之體認，有助於提升本所品保制度水準。

(二)本所核工組與台電公司已開始合作使用 GOTHIC 程式進行圍阻體熱水流分析申照工作，目前國內核一廠與核二廠圍阻體分析之專題報告已通過原能會核備。NAI 為 GOTHIC 原始發展者，且有與美國本土電力公司合作之豐富經驗，對於美國核能界與核管單位之最新發展與安全要求等，亦有較深之體認。經由本次合作，本所相關人員收穫甚豐，盼能有後續合作機會，進一步有效提昇本所相關技術能力。

(三)應持續進行爐心燃料佈局優化技術的發展。爐心燃料佈局設計優化技術在佈局設計自動化的領域一直是一項被關注的研究議題，本所使用基因演算法(genetic algorithm)建立爐心燃料佈局設計的優化技術及控制棒佈局設計的優化技術，目前已有初步的成果，建議持續發展此項技術，以提昇國內爐心燃料佈局的設計能力。

(四)應持續關注廠家慢速暫態分析方法的發展。廠家的慢速暫態分析方法並非一成不變，有時會因分析工具的進步而有所改變，或為了去掉一些過多的保守度而有所改變，建議在前往廠家訪問時，應持續關注其慢速暫態分析方法的發展，以做為國內發展相關分析方法的參考。

五、附　錄

(一) NAI 回應本所核工組對於 GOTHIC 程式之提問

Responses to Example Problem Questions

Prepared for INER

1) Basic Training Material

Comment:　Exercise- High Temperature Spray: Please explain the results of plots 1, 2 and 3.
Response: Each of the curves is described below.

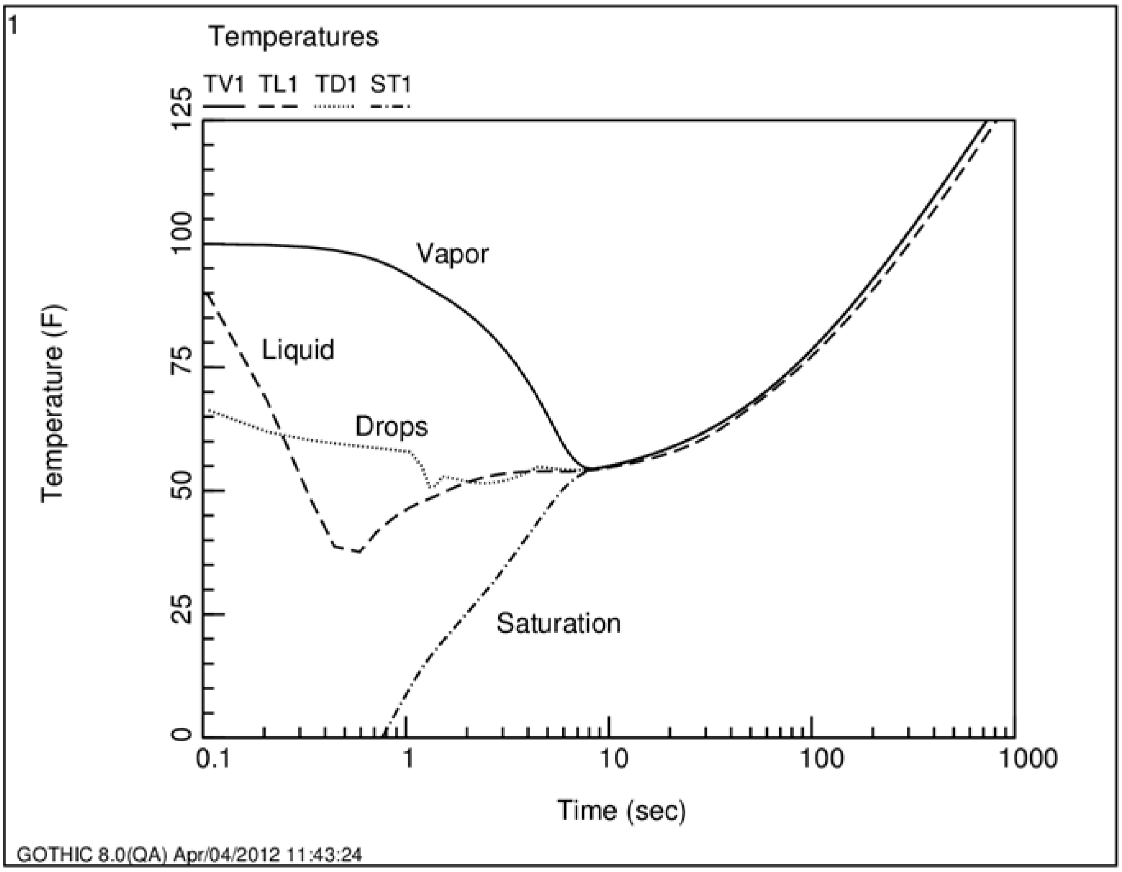


Figure 1: Phase Temperatures

Question 1) What happens to the atmosphere temperature from 0 - 10 seconds? 10 - 1000 seconds?
The vapor temperature decreases from 0-10 seconds because a large amount of liquid drops are evaporating. This cooling effect occurs because the droplets are at a temperature lower than the vapor and have a relatively large surface area.
Between 10 and 1,000 seconds the vapor temperature rises because relatively little phase change is

occurring. The vapor nears saturation around 10 seconds. Beyond this time more and more fluid is being added to the system leading to compression heating of the vapor phase.

Question 2) Why is the drop temperature much less than the injected drop temperature?
Recall that the drops are injected into a 10 ft high lumped volume. The drop temperature is the volume averaged drop temperature which includes droplets just injected near at top and droplets that have had significant time for evaporation before falling to the bottom. Heat from the drops and vapor contribute to the drop to vapor phase change. This reduces drop and vapor temperature.

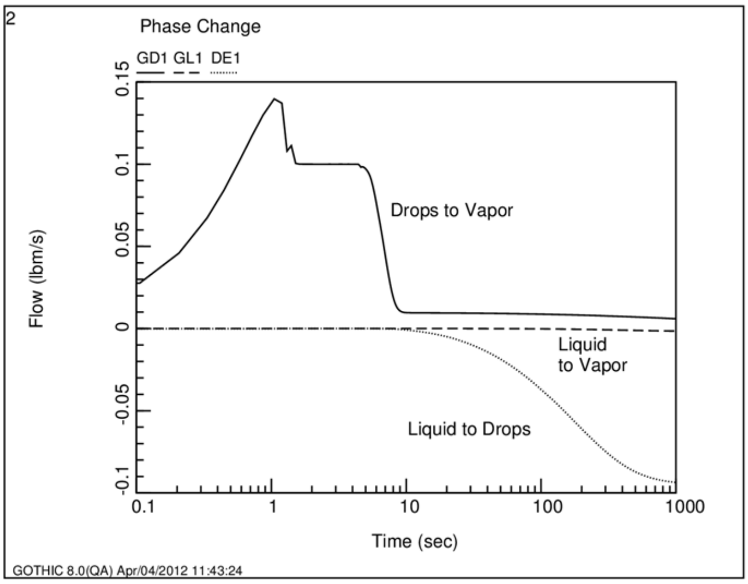


Figure 2: Phase Change Rates

The saturation temperature rises as drops are evaporated and steam is added to the vapor phase. When the vapor becomes close to saturated the evaporation rate of drops becomes small and drops begin to fall to the bottom and form a liquid pool. This begins near 10 seconds as shown in Figure 2.
Figure 3 shows the liquid and drop volume fractions. The sudden change in drop volume fraction near 1 second is due to excess evaporation of drops beyond equilibrium.

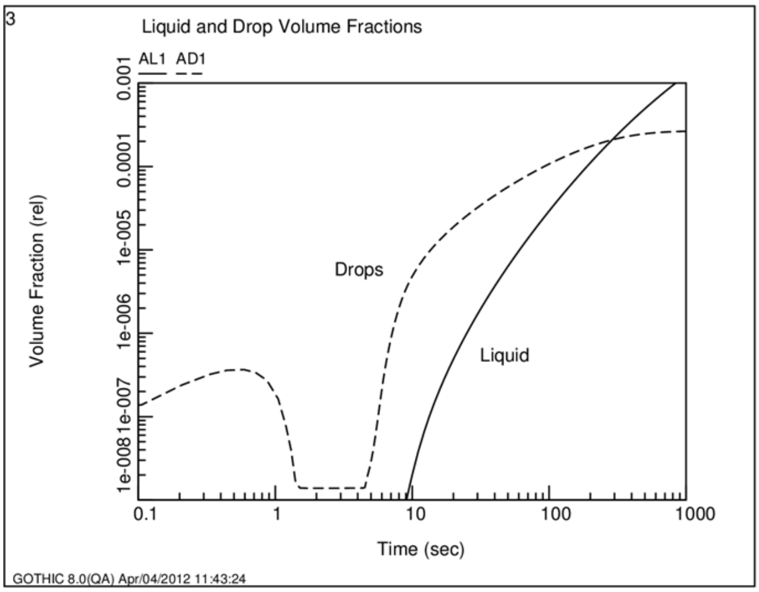


Figure 3: Drop and Liquid Volume Fractions

2) Cond./Hyd. Step Ratio

Comment: Conductor Parameters menu: For the parameter "Initial Temperature", please give an example to demonstrate how to use Cond./Hyd. Step Ratio to get the steady state temperature within a conductor.

Response: Using the Pipe heating problem: Make the pipe 0.5" thick to provide additional thermal mass to the problem. Change the conductor initial temperature to 5 F. Run the problem and examine both the pressure transient result and the conductor temperature profile at .1 seconds. Now run the case again with the following change: Create a new time domain for the first second of the transient. Change the DT ratio to 1e6 for this time domain. Run the new case and examine the pressure transient result and the conductor temperature profile.

The difference is that the DT ratio has reduced the amount of needed transient time to establish the conductor steady state temperature profile. The initial temperature specified by the user for conductor is uniform throughout the conductor. When the transient begins the conductor temperature profile responds to surface conditions. Using a high DT ratio effectively reduces the need to supply a precise initial temperature if steady state is desired because a high DT ratio accelerates the conduction solution.

From the User Manual

"This is the ratio of the time step for the conduction solution to the time step for the hydraulics solution. This parameter should be set to unity for simulation of a transient. With a sufficiently large value of this parameter, perhaps 10E6, a steady state temperature solution for the conductors can be obtained in one time step. This can be used to alter the initial temperature distribution in all conductors prior to the effective initiation of the thermal-hydraulic transient."

3) Boundary and Initial Conditions

Comment: For Boundary and Initial Conditions the gas volume fraction is defined relative to the gas volume. However, for the variable in RESULTS chapter, the gas volume fraction is defined relative to vapor volume. Please clarify it.

Response: The sum of liquid, drop, vapor, and ice volume fractions equals unity.

$$\alpha_l + \alpha_d + \alpha_v + \alpha_i = 1$$

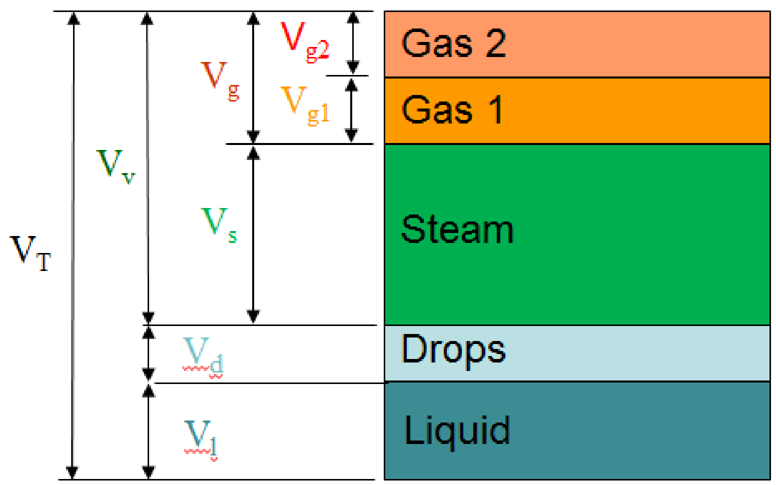
The vapor volume fraction α_v is defined as;

$$\alpha_v = \alpha_s + \sum \alpha_{g,i}$$

A gas fraction can be defined as a total volume fraction or the fraction of vapor.

$$\alpha_l + \alpha_d + \alpha_s + \sum \alpha_{g,i} + \alpha_i = 1$$

These relationships are valid in general. However upon insertion into boundary conditions and initial conditions the following guidelines apply.



- Liquid and Drop Fractions are relative to total volume ($\alpha_l = V_l/V_T$), ($\alpha_d = V_d/V_T$)
- Steam Volume Fraction is relative to vapor volume ($\alpha_s = V_s/V_v$)
- Gas Volume Fractions are relative to the gas volume ($\alpha_{g1} = V_{g1}/V_g$, $\alpha_{g2} = V_{g2}/V_g$)
- Steam and gas are well mixed in the vapor phase

Therefore if there is no steam present then the gas volume is equal to the vapor volume. The wording in the results chapter should be clarified.

4) Pipe Heating

Comment: Difference in pressure response.

Response: I found one difference. The containment volume is increased to 200 ft. height from 100 ft. height. This detail is not specified in the problem directions. Increasing the height in the containment volume increases the heat transfer rate to the pipe volume.

The height sensitivity stems from using the film roughening effect shown in equation 9.78 of the technical manual. If the condensation option is changed to DLM-M and rerun, a different time will be achieved. However, using the DLM-M model and changing the height from 100 to 200 makes very little difference in the time of reaching 3,000 psia.

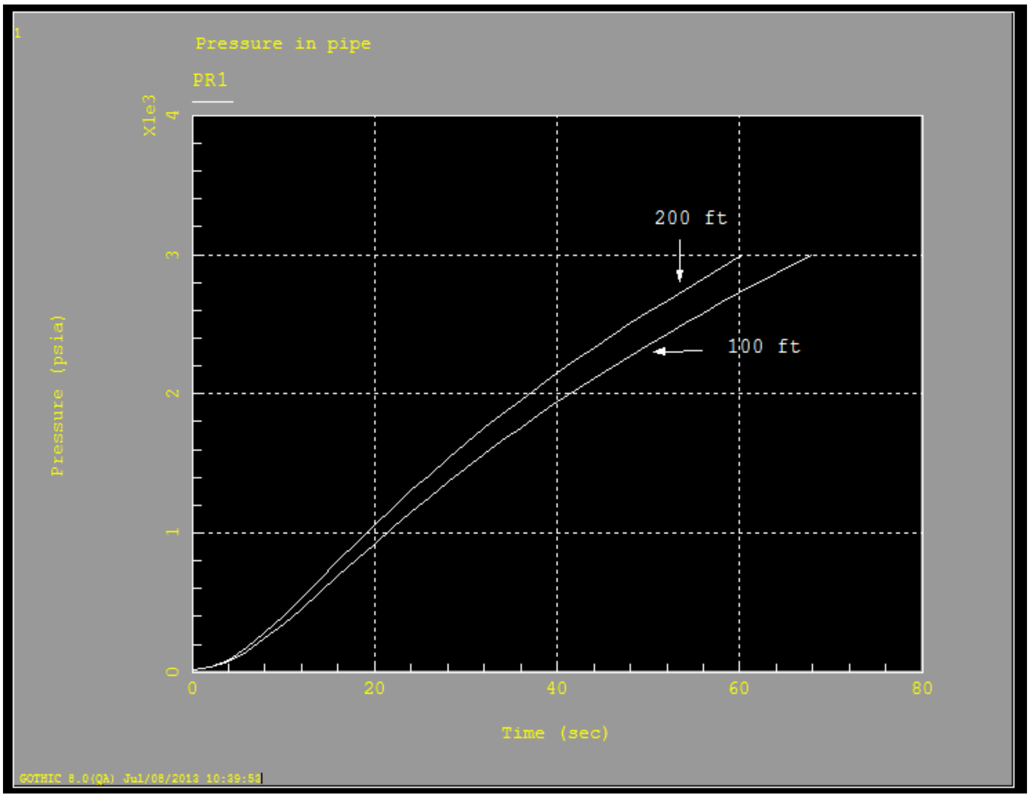


Figure 4: Response Difference due to Volume 2 height

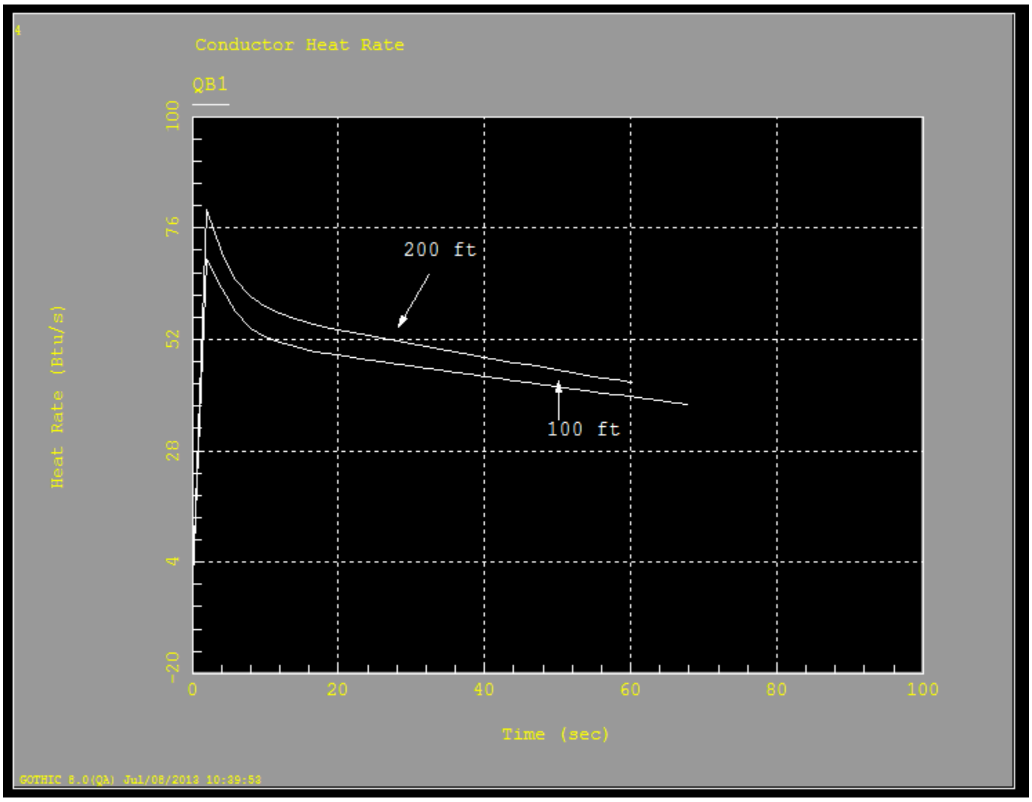


Figure 5: Heat Transfer Rate

Comment: Why is modeling of elasticity not able to be done for a lumped volume?
Response: It could be done but this is not intended as a lumped volume does not have a defined geometry. In very simple one-dimensional cases this may not matter. In general however it is better to subdivide the volume and define the volume boundaries.

Comment: Please explain the option of Position Cond. Marker.
Response: Use this option to position thermal conductors in subdivided volumes. A conductor location can be changed after being set, so this option also serves as a conductor replacement option in the sub volumes diagram. Use this option to replace a spanned conductor and the spanned designation is removed.

Comment: How to let the calculation continue when fluid pressure exceeds 3000 psia?
Response: 3000 psia approaches the critical pressure. Fluid properties in GOTHIC are not accurate in this region. To date there is no critical pressure modeling in GOTHIC. This feature may be added in the future for critical H_2O modeling.

Comment: Where is the thermal expansion coefficient for water specified?
Response: Thermal expansion for water is handled in GOTHIC by the density dependency on pressure and temperature. These fluid properties are built into GOTHIC, negating the need to specify a thermal expansion coefficient.

5) Tank Condensation 3D

Comment: The vapor temperature response result at cell 30 is different from that provided in gothic file.

Response: The liquid volume fraction initial conditions in the supplied model contained a global entry for volume two of 100% liquid volume fraction, followed by cell specific initial conditions. If the model is changed by removing this entry the results agree. I realized the difference by comparing (line graph) the liquid height in each volume. This highlights an important technique for troubleshooting problems in GOTHIC. The analyst will find it very helpful to plot variables related to the issue which may lead to a solution as to why the model results are different than expected.

Table 1: Initial Conditions

Volume Initial Conditions							
Vol #	Total Pressure (psia)	Vapor Temp. (F)	Liquid Temp. F	Relative Humidity (%)	Liquid Volume Fract.	Unused	Unused
def	14.7	80.	80.	60.	0.	0.	0.
1	15.	80.	80.	100.	0.5625		
2s	15.	80.	80.	100.	1.		
2s1	15.	80.	80.	100.	1.		
2s2	15.	80.	80.	100.	1.		
2s3	15.	80.	80.	100.	1.		
2s4	15.	80.	80.	100.	1.		
2s5	15.	80.	80.	100.	1.		
2s6	15.	80.	80.	100.	1.		
2s7	15.	80.	80.	100.	1.		
2s8	15.	80.	80.	100.	1.		
2s9	15.	80.	80.	100.	1.		
2s10	15.	80.	80.	100.	1.		
2s11	15.	80.	80.	100.	1.		
2s12	15.	80.	80.	100.	1.		
2s13	15.	80.	80.	100.	1.		
2s14	15.	80.	80.	100.	1.		
2s15	15.	80.	80.	100.	1.		
2s16	15.	80.	80.	100.	1.		
2s17	15.	80.	80.	100.	0.5		
2s18	15.	80.	80.	100.	0.5		
2s19	15.	80.	80.	100.	0.5		
2s20	15.	80.	80.	100.	0.5		

6) Boiler/Feedwater Exercise

Comment: In Case A, B, and C, can’t get the same liquid-to-vapor change rate as that from gothic file.

Response: Case A, B, and C are appropriate. The Liquid to Vapor change rate is very noisy and expected to look a bit different in each case. The time average change rate calculated using a control variable shows similar results.

The results for phase change in this problem are sensitive to the vent pipe inertia length. In addition, the specified graphics interval of 20 seconds does not produce precise results. This is a situation in which a time averaged result, as shown in the problem, is preferable.

Comment: In Exercise 3-Case 3cs, a 3D connector is used between a lumped volume (diffuser) and a subdivided volume (boiler). In the manual, it is said that only the elevations are required to be compatible. How to match the grid line of the subdivide volume with the lumped volume?

Response: The bottom elevation of the boiler must equal the top elevation of the diffuser. The boiler elevation is specified in the control volumes table. For the diffuser, the top elevation is the elevation plus the height (both are specified in the control volume table).The XY gridlines would need to match up if both volumes were subdivided. However, the diffuser volume is lumped and the exterior dimensions (XY) match for both volumes.

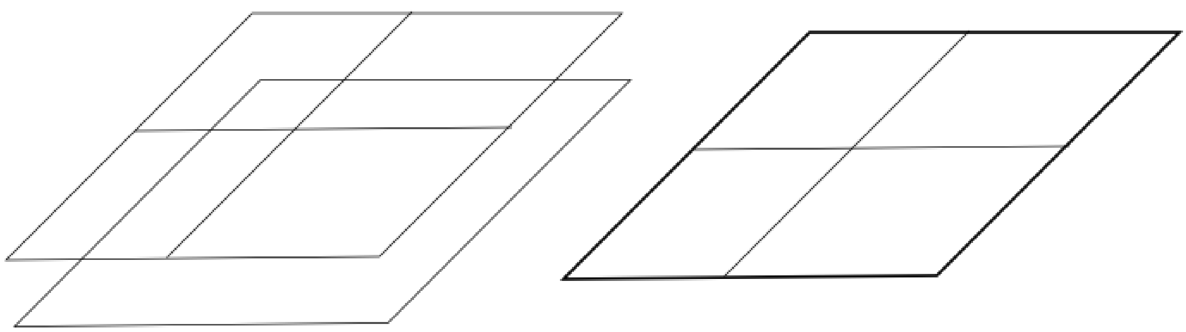


Figure 6: Example of Matching Volume Boundaries for 3D Connector

The use of a 3D connector between a lumped and subdivided volume (a diffuser) is an important technique available to create a uniform entering velocity profile.

7) Control Variables

Comment: When using the control variables, please clarify the difference between the variable: junction vapor flow and the variable: junction vapor continuity flow.

Response: The junction flow is calculated as rho*alpha*velocity*area. For single phase flow, the only difference is that the upstream density is used for continuity and average density is used for momentum. In addition, for two-phase flow, alpha is the upstream volume fraction, accounting for the pool height relative to the end elevation and height for the continuity flow. For the momentum flow, the volume fraction is calculated as indicated in the TM. It basically accounts for the time that it takes to fill the flow path with the upstream conditions.

8) Flow Path Losses

Comment: In the handout, it is stated:

$$K_{total} = \left[K_{forward}\ or\ K_{reversed}\right] + K_{exit} + K'_{valve} + K_{friction}$$

Is $K_{friction}$ the upstream or downstream friction loss?

Response: In general, a frictional pressure loss is defined in the following way:

$$\Delta P_{fric} = \frac{1}{2}\frac{fL_f}{D_h}\rho\ u\bar{u}$$

Where $\bar{u} = u\frac{\rho^*}{\bar{\rho}}$. For consistency with the mass flow rate used in the mass balance equations, ρ^* is the upstream fluid density. $\bar{\rho}$ is the average of the upstream and downstream fluid densities. Attachment A to this document contains guidelines and methodology on the use of loss coefficients.

Comment: What is the significance of K_{exit} and $K_{forward}$ (or $K_{reversed}$)? Which pressure drop is calculated? Is it the pressure drop between center of upstream volume and center of downstream volume?

In the user manual for Flow Path Parameters-3, it is described as:

$$\Delta P = \left[K + K_{exit}\right]\frac{\rho}{2}\mathrm{v}^2$$

Where K the is forward or reverse loss coefficient. Why is $K_{friction}$ not included here?

Response: Friction loss is accounted for by the following equation:

$$\Delta p = \frac{fl}{D_h}\frac{\rho v^2}{2}$$

The friction length is specified along with a friction factor as a flow path parameter. $K_{forward}$ and $K_{reversed}$ describe the directional loss to account for forward and reverse flow through a flow path. $K_{forward}$ is applied to flow moving from side A to side B of a flow path. $K_{reversed}$ is applied to flow moving from side B to side A of a flow path. These coefficients need not be the same. For example a series of flow contractions in one direction is a series of flow expansions in the other direction.

K_{exit} has important application to critical flow modeling. The critical flow model uses the loss coefficient for a flow path to obtain the stagnation pressure upstream of the choke plane and a discharge coefficient to use as a multiplier on the calculated choked flow from a flow path. If the flow is choked, the discharge coefficient is calculated from the exit loss coefficient. If the flow is not choked, the exit loss coefficient is added to the flow path loss coefficient to obtain the total loss for the flow path.

The user manual is therefore separating losses applied before the choke plane with losses applied after the choke plane. The K value may be thought of as total loss in this equation.

9) Choked Flow

Comment: In the handout for choked flow loss coefficient, it is described:

$$F_{choke} = F_{\max} \times Min\left(1, K_{exit}^{-0.5}\right)$$

What is the significance of this equation?

Response: Another way to express the same relationship is:

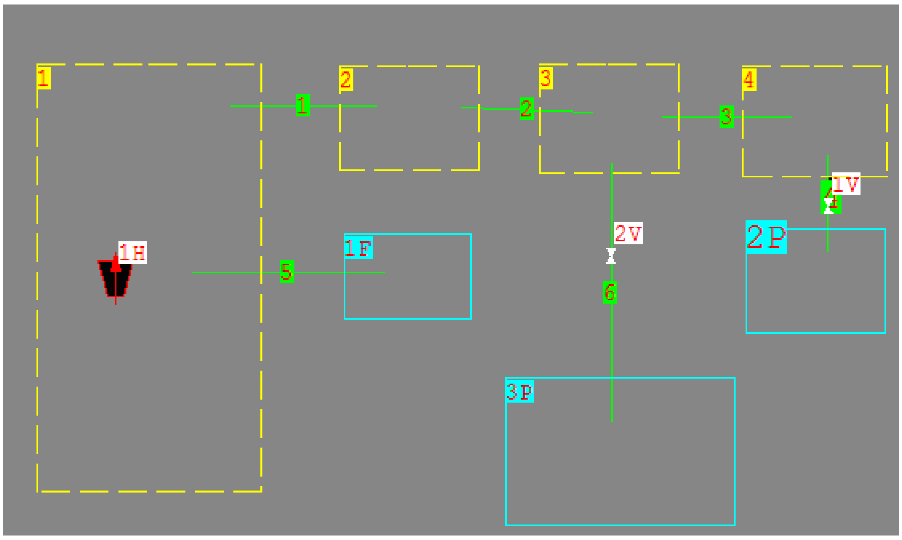
Where the discharge coefficient C_d is calculated by:

$$C_D = Min(1, 1/\sqrt{k_{exit}})$$

The critical flow model gives the maximum discharge rate assuming an isentropic process. In real flow situations, the flow may not be isentropic and the discharge rate will be less than the maximum rate. To account for this, the user may supply an exit loss coefficient which is used to calculate a discharge coefficient.

10) Critical Flow (HELB Model)

Comment: For the following model for main steam line break, steady state has been run for 1000 seconds, then a break occurs through quick opening of valve 2. Valve 4 is tripped to close at 1000 second. We have specified critical flow model at flow path 6, do we still specify the critical flow model at other flow paths?



Response: If you want to know if the critical flow model is actually limiting flow, check the critical flow flag written to the .SOT file as the last column of output under Junction Data. If the value is zero, a critical flow calculation was not requested. If the value is 1, the TABLES option was invoked but did not limit the flow. If the value is 2, either the HEM or SEM option was invoked but did not limit the flow. If these values are negative, then critical flow did limit flow. This information is only available for each output edit. To get more information, capture the variable “icrtfm” in a control variable. Then you will have the value of this flag at each graphics interval.
It is recommended to use the choking model only on the flow paths where choking might be expected. Keep in mind that it generally takes up to downstream pressure ratio greater than 1.8 for choking in the vapor phase. The HEM and SEM models can significantly slow the run speed.

11) Positive Pressure Period

Comment: Error for running PPP (positive pressure period) file in GOTHIC 8.0 using an input file from GOTHIC 7.1.2013
Response: On upgrading this file to 8.0 the following error was found in the SER file:
Nan error in control variable 3
The value of the radicand is -0.000717 which results in an imaginary number. This error may be avoided by setting a minimum limit on CV 2 to something like 1e-8 so CV 3 never receives a zero or negative number.   The model then runs to completion.

12) Component Volume Fractions Example

Create a lumped control volume with the following initial conditions:

- **Liquid volume fraction = 0.5**
- **Liquid/Vapor Temperature = 212F**
- **Relative Humidity = 50 % (equivalent to 50% steam volume fraction at Tsat=212)**
- **Gas # 1 (air) fraction =0 (fraction of vapor)**
- **Gas # 2 (O2) fraction =0.5 (fraction of vapor)**
- **Gas # 1 (N2) fraction =0.5 (fraction of vapor)**

The initial condition menu should like Figure 7.
GOTHIC will not allow the user to specify nonphysical conditions. If the temperature is below Tsat, say 80 F, specifying relative humidity of 100% will not provide a steam volume fraction of 50% because the partial pressure is much too low.
Run the model and plot liquid, vapor, steam, O2, and N2 volume fractions. Notice that the gas volume fractions are decreasing. This is because of pool evaporation (T=Tsat). See Figure 8. To remove phase change effect set the Liquid/vapor interface area (L/V IA) to zero. Now run the model again. Now you should see constant volume fractions that were specified in the initial conditions menu. See Figure 9.
Make a new graph and plot the Dry volume fractions of O2 and N2. The results are different because the volume fractions are not total volume fractions but rather the fraction of non-condensable gases. See Figure 10.
The example demonstrates the guidelines for entering volume fractions. Steam and gases are volume fractions of the Vapor volume. The results show the volume fractions on a total volume basis.

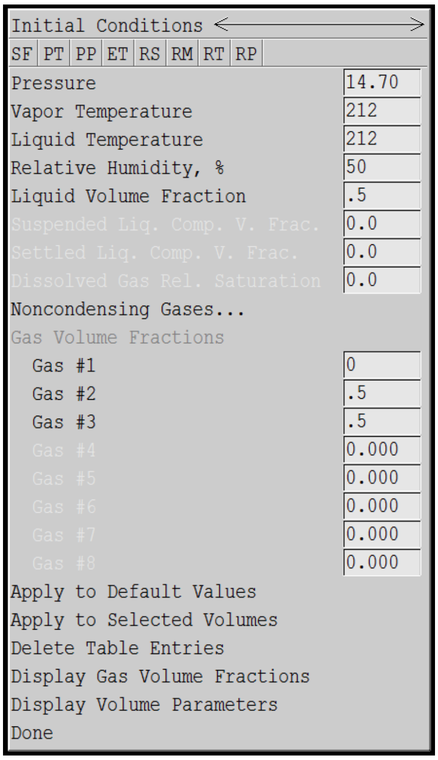


Figure 7: Initial conditions

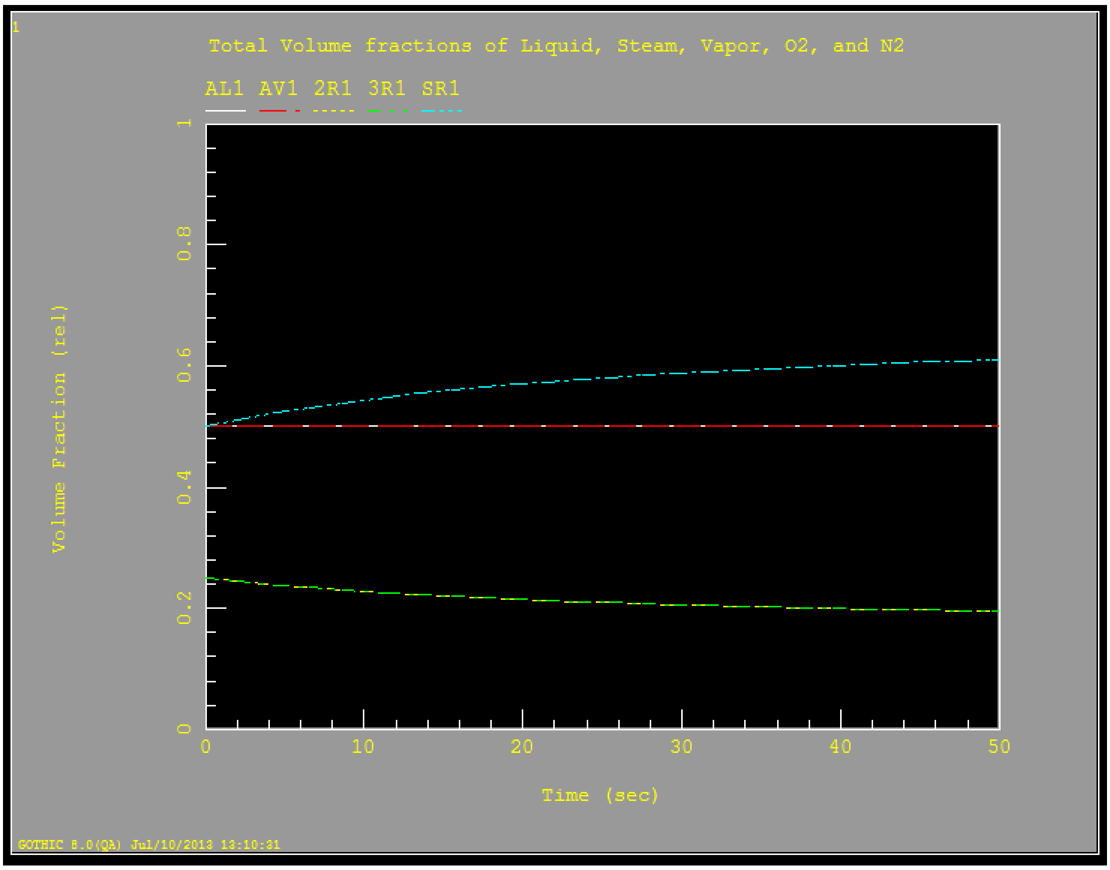


Figure 8: Volume fractions

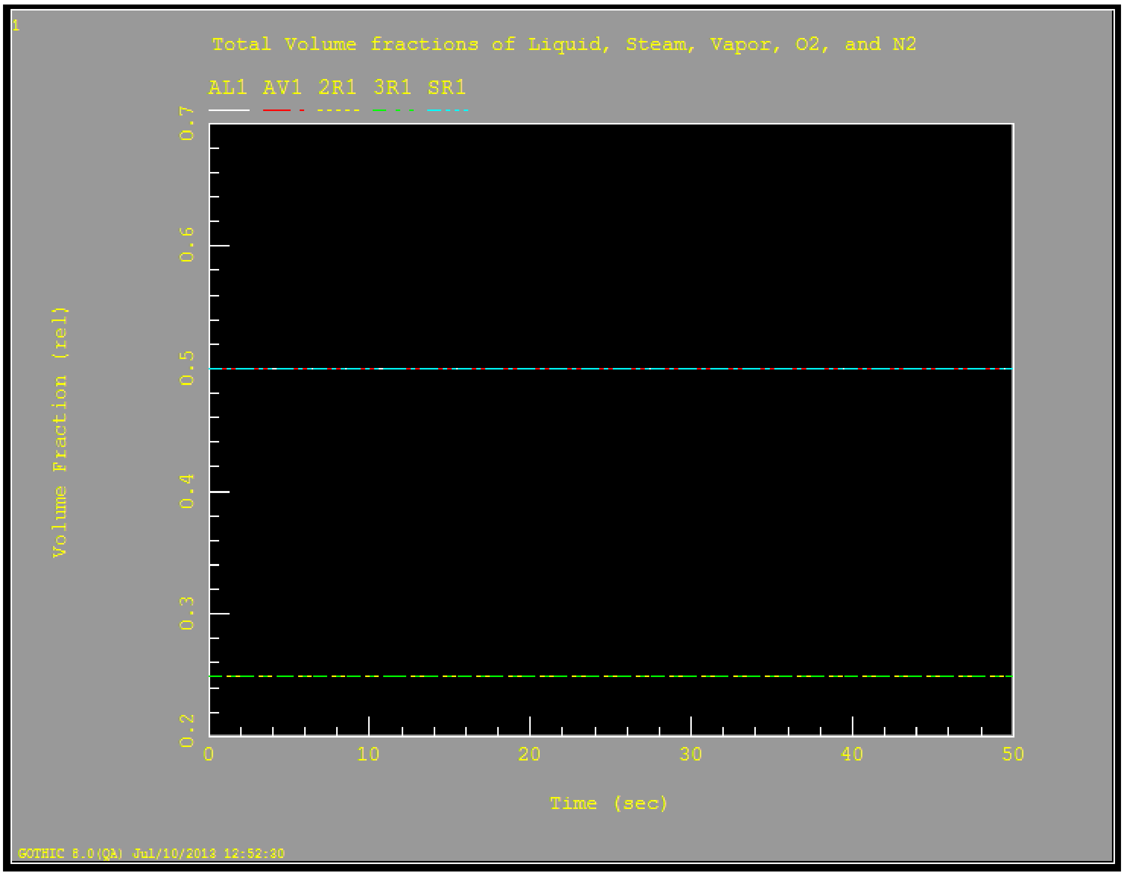


Figure 9: Volume fractions

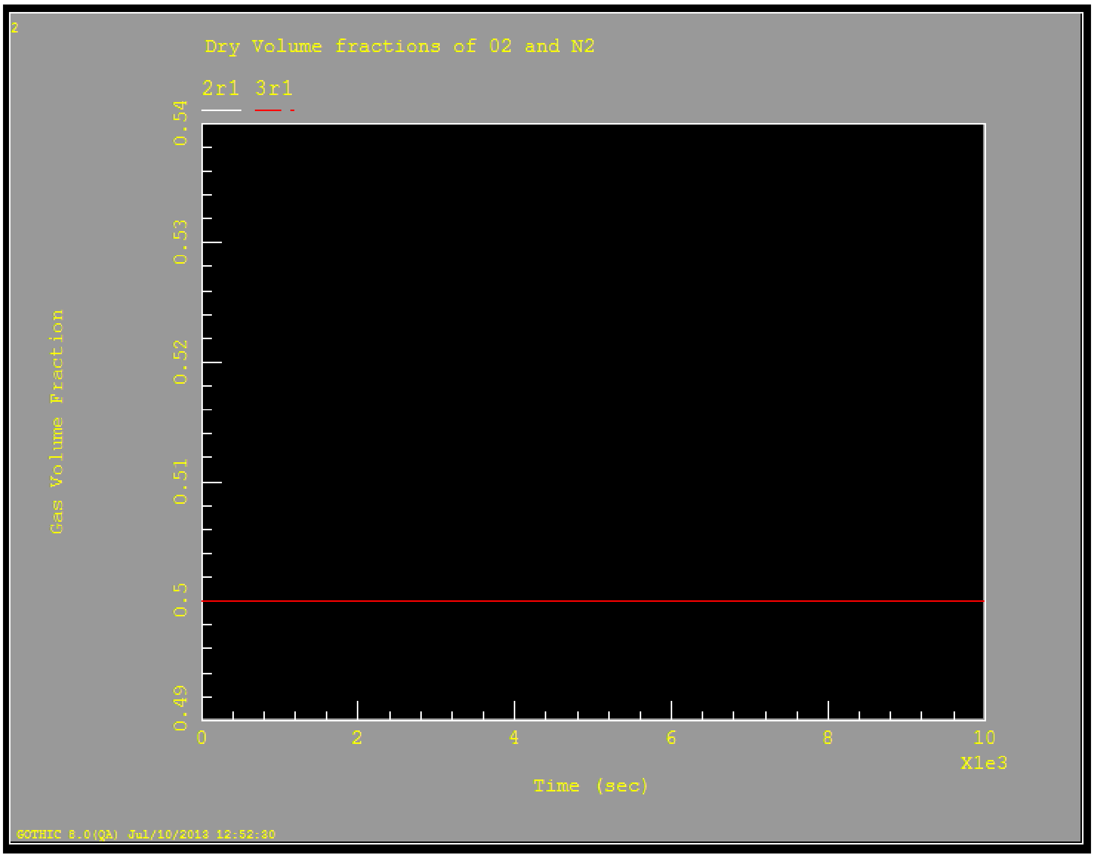


Figure 10: Dry volume fractions

(二) EPRI 每季寄送之 Bug Summary 範例

GOTHIC Problems Summary

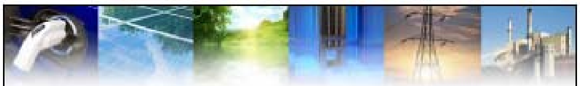
Error Classifications

NAI	*EPRI*
0 - No effect on users	*Low - Functional failure, user inconvenience, cosmetic error*
1 - User inconvenience	*Med - No results or results that are obviously meaningless or incorrect*
2 - Functional failure	*High - Possible misleading results or documentation, Part 21 evaluation required*
3 - Code quits, available result good	
4 - Code quits, results obviously bad	
5 - Code runs, results obviously bad	
6 - Safety concern, depending on application	
7 - Safety concern, 10CFR21	

ID	*Status*	*Error Class NAI*	*Error Class EPRI*	*Affected Versions*	*Problem Description*	*Workaround*	*Fixed In*
8.0-296	In Review	1	Low	6.1-8.0	Although the User Manual says that the Tmax function works for gas variables, in version 8.0, it only works for gas variables Diffus, Rg and Hg.	None.	8.1
8.0-305	Closed	3	Low	8.0	GOTHIC8.0 introduced forcing functions for volume porosity which may be used in some specialized applications. In cases with extreme changes in porosity, the code may experience degraded numerical performance and ultimately terminate because the pressure solution will not converge. This is the result of not restoring the old time value of volume porosity correctly when a calculational backup occurs.	Use a smaller max time steps to avoid calculational backups in cases with extreme changes in porosity.	8.1
8.0-307	Open	M	Low	4.0-7.2b	In versions 7.2b and earlier, simulations with long transient time (>1.0e5 seconds) and small specfied minimum time step size (1.0e-8 seconds) may encounter an infinite loop in integration of the valve travel curve. In version 8.0, the situation could occur at longer transient times (>1.0e7 seconds).	Increase the size of the minumum time step in the time domains with long simulation times.	8.1

Tuesday, July 02, 2013 *Page 1 of 3*

(三) NAI 福島事故 GOTHIC 模式簡報：抑壓池溫度層化與反應器廠房氫氣濃度分佈



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Fukushima GOTHIC Analyses

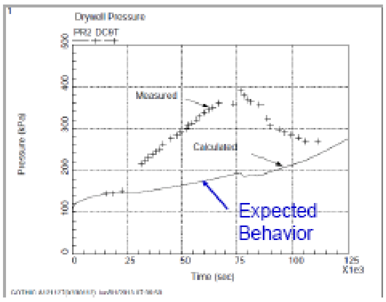
EPRI Safety Technology Joint Session
June 5, 2013

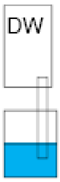
Tom George
Zachry Nuclear Engineering
Numerical Applications Division

Objective

- Investigate event phenomena details
  - Drywell temperature and gas concentration distribution
  - Wetwell performance (stratification, mixing, bypass, etc.)
  - Reactor Building hydrogen distribution
    - Wetwell venting
  - Tsunami building flooding

Wetwell Performance – Unit 3





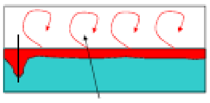
Typical Lumped Containment Model

1F3 Event Scenario
BASF Project – OECD-NEA Benchmark

- 3/11-14:47 (0s) Earthquake
- 3/11-15:05 (1,080s) RCIC manual start – 4.1 kg/s exhaust flow
- 3/11-15:25 (2,280s) RCIC trip
- 3/11-15:38 (3,060s) SBO
- 3/11-16:03 (4,560s) RCIC manual start
- 3/12-11:36 (74,790s) RCIC trip
- 3/12-12:06 (76,740s) Wetwell spray start – 13.8 kg/s
- 3/12-12:35 (78,480) HPCI activated
- 3/13-02:42 (129,300) HPCI stopped
- 3/13-05:08 (138,680) Wetwell spray stopped

Possible Cause for Pressurization
Suppression Pool Stratification

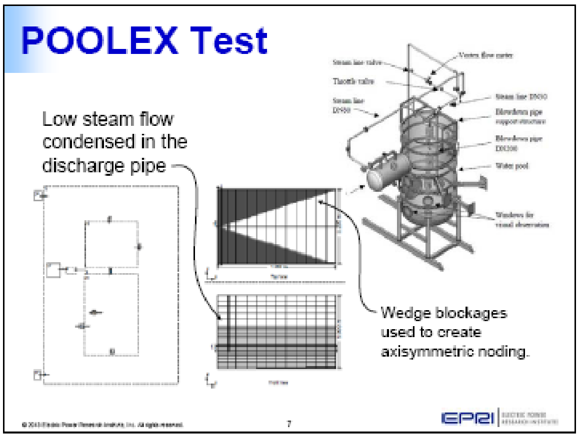
- Pool stratification has been considered as a possible cause for the containment pressure rise
  - Localized steam release via RCIC exhaust or SRV
  - Thermal plume rises to surface and spreads
  - High surface temperature results in high gas space temperature and steam concentration

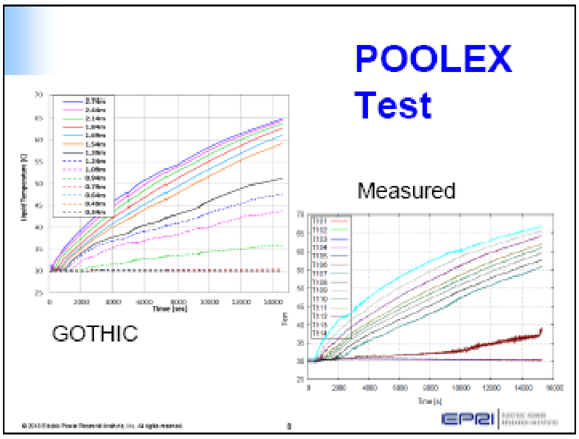


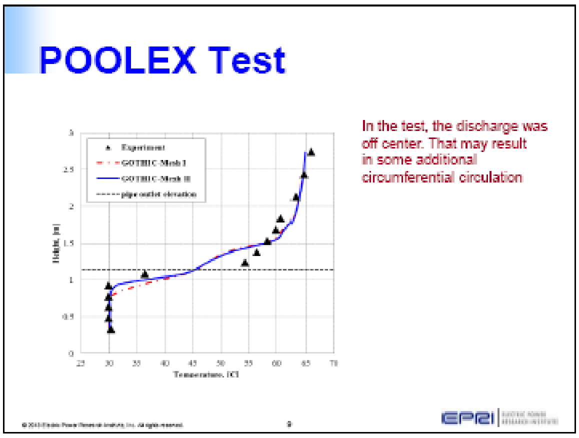
Evaporation and Heat Transfer

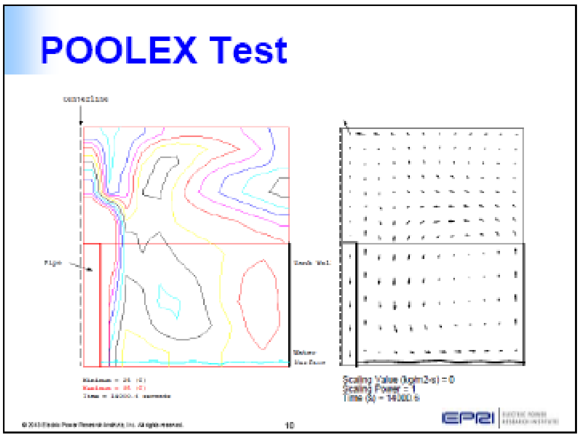
Pool Stratification Validation for GOTHIC

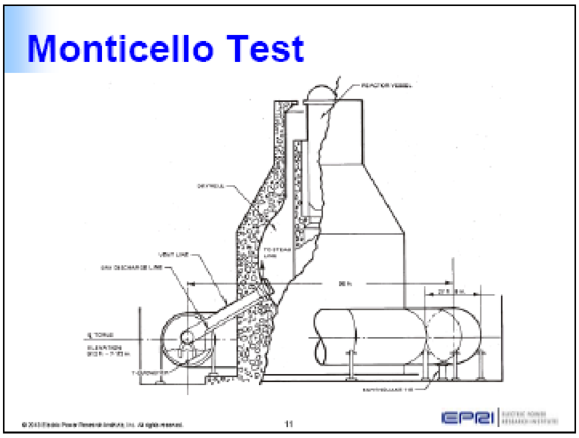
- POOLEX Test
  - Low steam release through single vertical vent
  - Open Tank
  - Lappeenrenta University (Finland)
- Monticello SRV Test
  - Mark 1 Containment
  - Continuous steam release from a single SRV

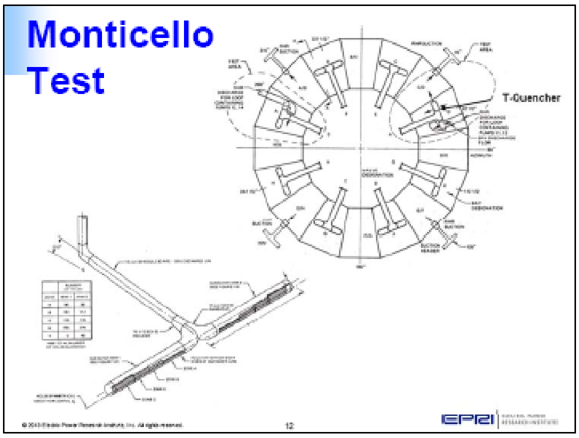

POOLEX Test
Low steam flow condensed in the discharge pipe
Wedge blockages used to create axisymmetric noding.
7

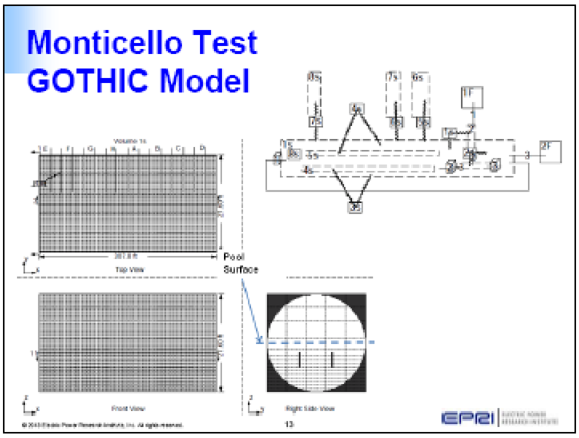

POOLEX Test
Measured
GOTHIC
8

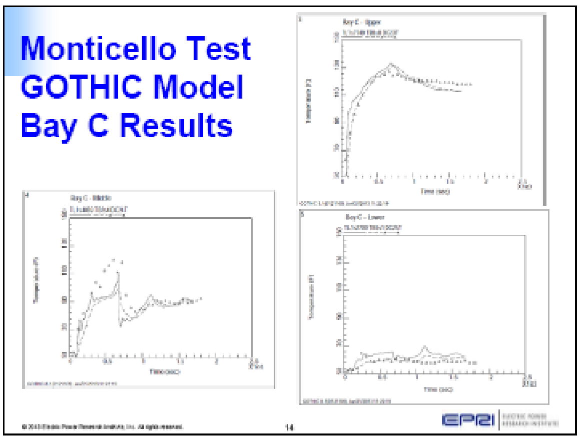

POOLEX Test
In the test, the discharge was off center. That may result in some additional circumferential circulation
Experiment
GOTHIC-Mesh I
GOTHIC-Mesh II
pipe outlet elevation
Temperature, [C]
9

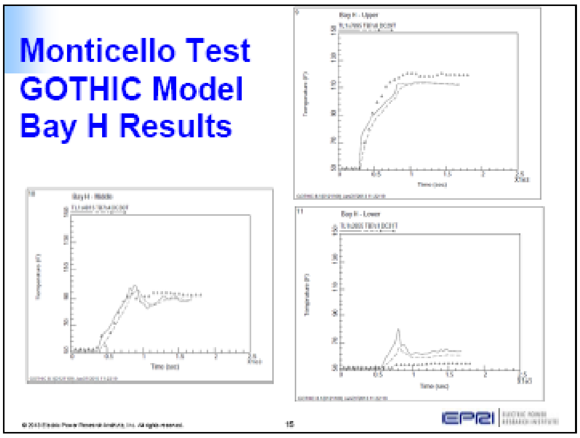

POOLEX Test
centerline
10


Monticello Test
REACTOR VESSEL
DRYWELL
VENT LINE
T-QUENCHER
11


Monticello Test
T-Quencher
12


Monticello Test
GOTHIC Model
Pool Surface
Top View
Front View
Right Side View
13


Monticello Test
GOTHIC Model
Bay C Results
14


Monticello Test GOTHIC Model Bay H Results
Bay H - Upper
Bay H - Middle
Bay H - Lower
Time (sec)
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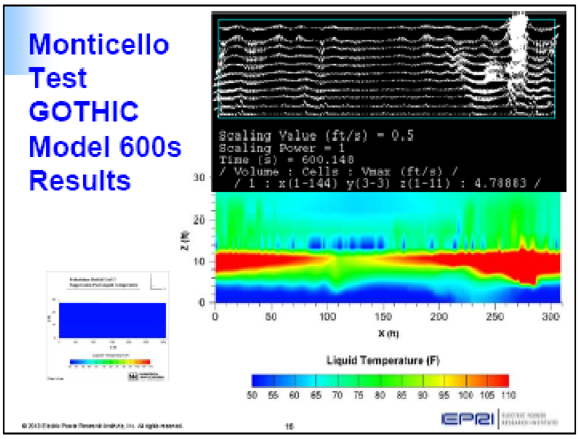
15


Monticello Test GOTHIC Model 600s Results
Scaling Value (ft/s) = 0.5
Scaling Power = 1
Time (s) = 600.148
/ Volume : Cells : Vmax (ft/s) /
/ 1 : x(1-144) y(3-3) z(1-11) : 4.78883 /
X (ft)
Liquid Temperature (F)
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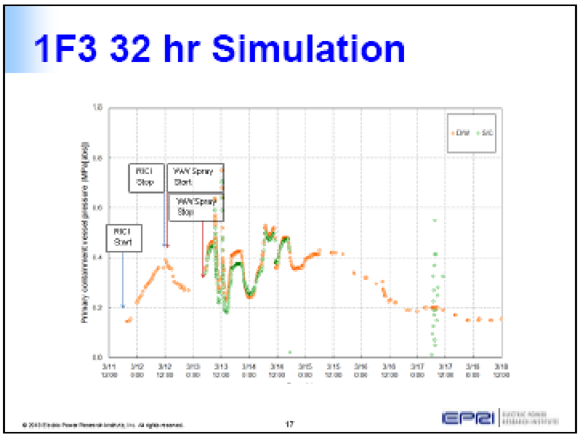
16


1F3 32 hr Simulation
RICI Stop
W/W Spray Start
W/W Spray Stop
RICI Start
D/W
S/C
Primary containment vessel pressure (MPa[abs])
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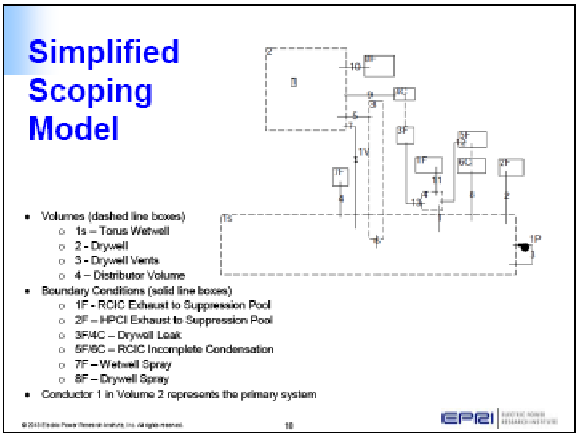
17


Simplified Scoping Model
Volumes (dashed line boxes)
1s – Torus Wetwell
2 - Drywell
3 - Drywell Vents
4 – Distributor Volume
Boundary Conditions (solid line boxes)
1F - RCIC Exhaust to Suppression Pool
2F – HPCI Exhaust to Suppression Pool
3F/4C – Drywell Leak
5F/6C – RCIC Incomplete Condensation
7F – Wetwell Spray
8F – Drywell Spray
Conductor 1 in Volume 2 represents the primary system
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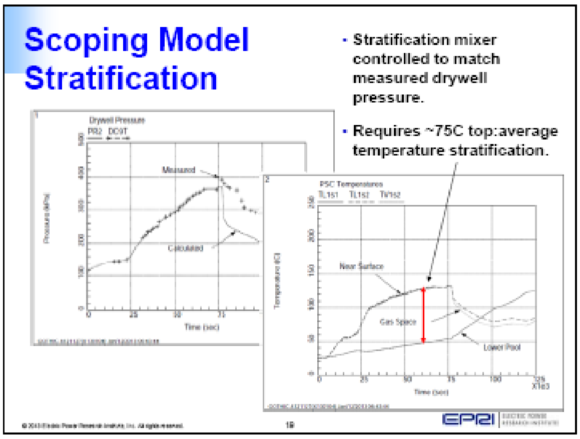
18


Scoping Model Stratification
Stratification mixer controlled to match measured drywell pressure.
Requires ~75C top:average temperature stratification.
Drywell Pressure
Measured
Calculated
PSC Temperatures
Near Surface
Gas Space
Lower Pool
Time (sec)
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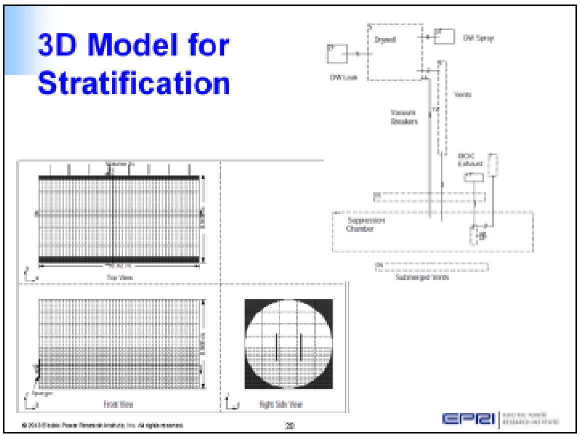
19


3D Model for Stratification
Drywell
DW Spray
DW Leak
Vents
Suppression Chamber
Submerged Vents
Top View
Front View
Right Side View
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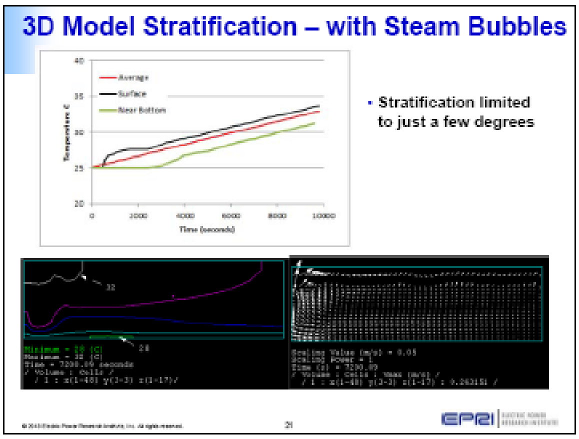
20


3D Model Stratification – with Steam Bubbles
Stratification limited to just a few degrees
Average
Surface
Near Bottom
Temperature C
Time (seconds)
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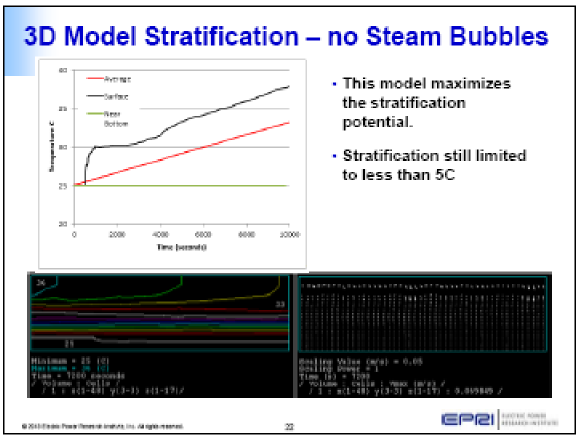
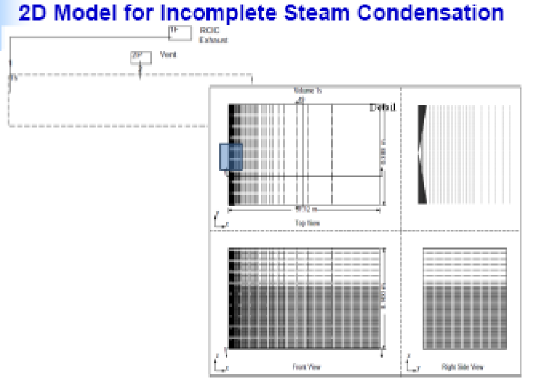
21


3D Model Stratification – no Steam Bubbles
This model maximizes the stratification potential.
Stratification still limited to less than 5C
Average
Surface
Near Bottom
Temperature C
Time (seconds)
© 2013 Electric Power Research Institute, Inc. All rights reserved.
22

Possible Cause for Pressurization
Incomplete Condensation

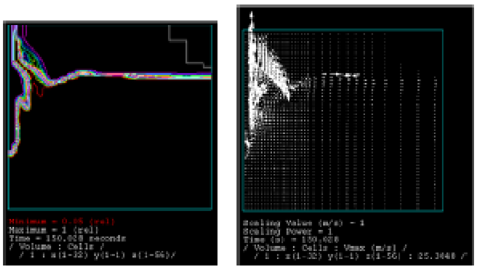
- At high steam injection rates some of the steam may escape the pool.
- Increased temperature and steam content in the gas space ➔increase containment pressure.

2D Model for Incomplete Steam Condensation

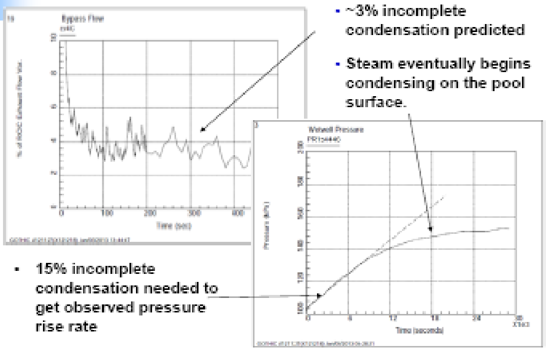


2D Model for Incomplete Steam Condensation

- Near sparger void and velocity distribution



2D Model for Incomplete Steam Condensation

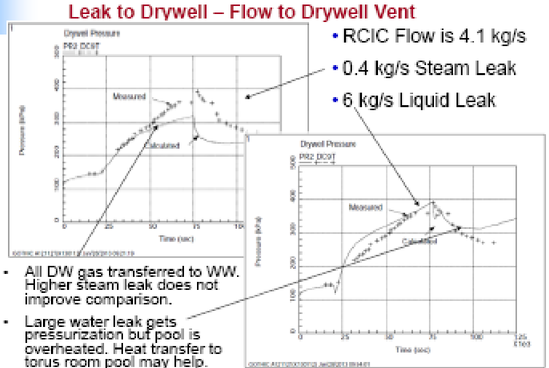


- ~3% incomplete condensation predicted
- Steam eventually begins condensing on the pool surface.
- 15% incomplete condensation needed to get observed pressure rise rate

Possible Cause for Pressurization
Steam or High Temperature Water Leak to the Drywell

- Steam carries drywell gas to the wetwell.
- Additional heating of the pool leading to gas space heating, pool evaporation and pressure rise.

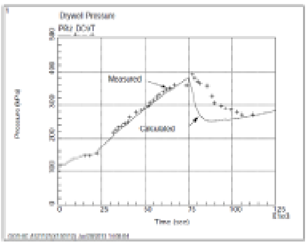
Possible Cause for Pressurization
Leak to Drywell – Flow to Drywell Vent



- RCIC Flow is 4.1 kg/s
- 0.4 kg/s Steam Leak
- 6 kg/s Liquid Leak
- All DW gas transferred to WW. Higher steam leak does not improve comparison.
- Large water leak gets pressurization but pool is overheated. Heat transfer to torus room pool may help.

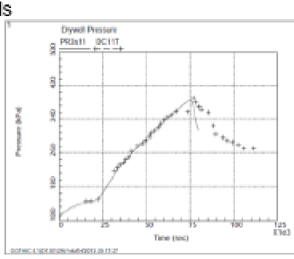
Leak to Drywell and Drywell to Wetwell Leak

- Simplified Scoping Model
  - 0.28 kg/s steam leak to DW
  - Restricted pool surface heat and mass transfer.
    - Simulates stratification of the gas space.

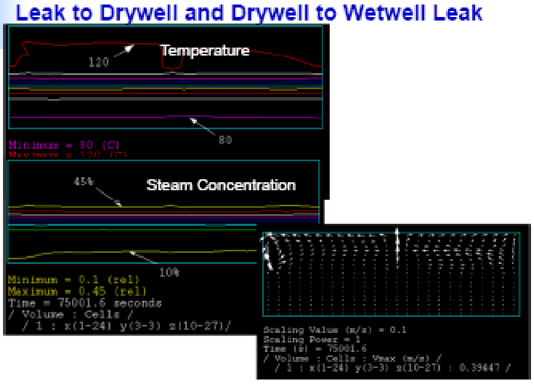


Leak to Drywell and Drywell to Wetwell Leak

- 3D Model
  - 0.28 kg/s DW leak
  - No restriction on pool surface heat and mass transfer.
    - Built in GOTHIC models
  - Initial 0.02 kg/s leak, ramped to 0.28 kg/s from 20,000 to 25,000s
  - Includes 1D DW model.

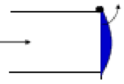


Leak to Drywell and Drywell to Wetwell Leak



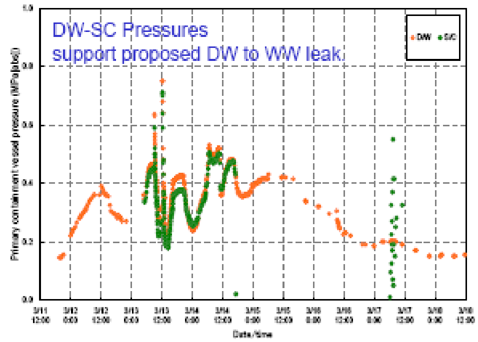
Leak to Drywell and Drywell to Wetwell Leak

- Best agreement with measured containment pressurization
- Torus surface temperature reaches 120C, high enough to melt polymer shoe sole material
- Requires a DW to WW leak area of 22 cm^2. This is larger than NRC allowed Mark I limits (5.1 cm^2, NUREG-0800).
  - One vacuum breaker open to 1 degree swing would allow more than 55 cm^2 leak area.



PCV pressure

Unit 3



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Comments

- Predicted cooling rate induced by the WW spray is much higher than measured.
  - Uncertainty in spray rate?
- Analysis neglects steam from SRVs.
  - Most of the decay heat is accounted for in the assumed RCIC exhaust flow.
  - Additional steam from the SRVs may reduce size of steam leak and WW leak area needed to match observed pressurization.

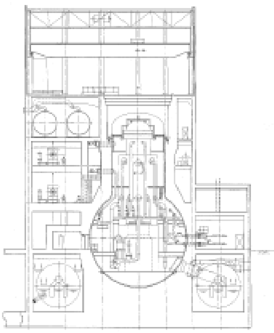
Conclusion

- Good agreement with data for Monticello and POOLEX tests.
- Treatment of steam bubbles may need additional work
- Pool stratification not likely responsible for 1F3 pressurization
- Gas space stratification important if there is a leak to the gas space.

Fukushima Unit 1 Reactor Building Performance

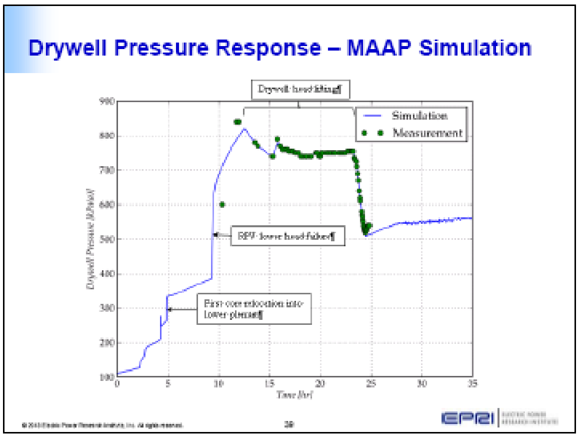
Objective

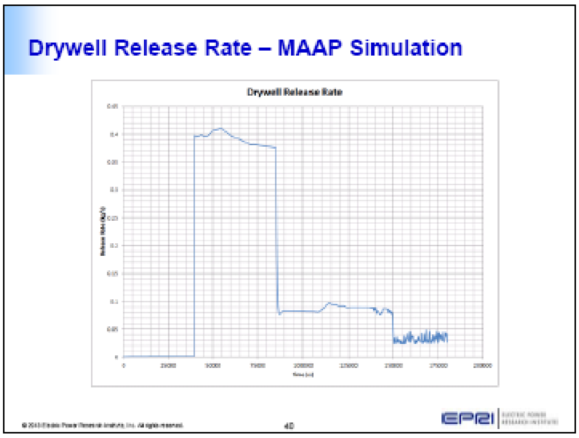
- Use 3 dimensional GOTHIC model to predict combustible gas concentration in the Unit 1 Reactor Building.
- Investigate possible gas contribution from the venting of the suppression pool.
- Sensitivity cases for location of the leak to the Reactor Building.

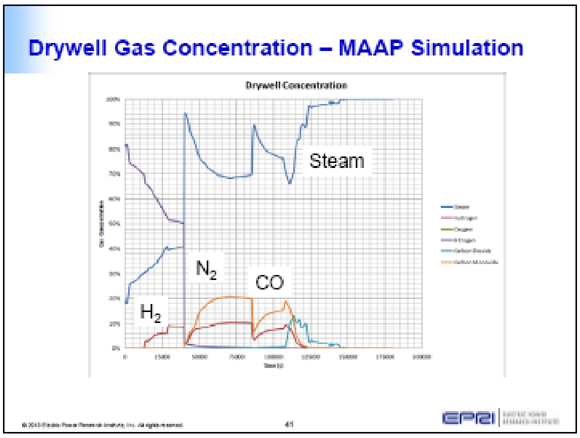


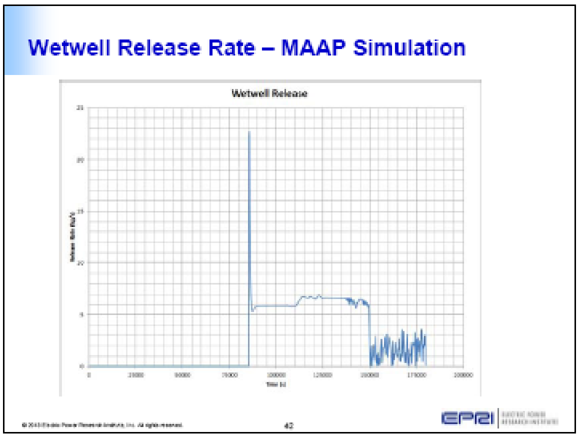
Estimated Time Line – MAAP Analysis

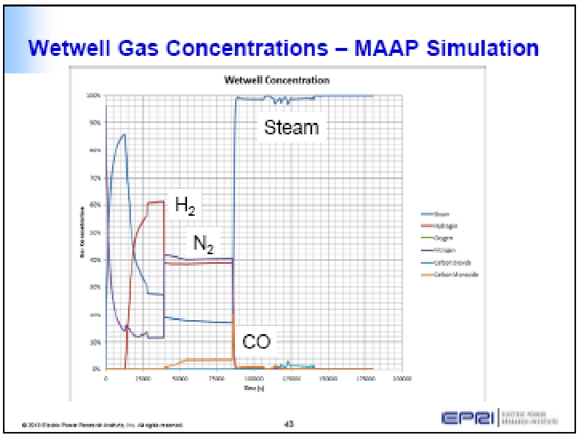
- March 11 – 14:46 – Earthquake
- ~+55 minutes – Station Blackout
- ~+3hr 45 minutes – SRV steam/hydrogen leakage to DW
- ~+5 hours – core relocation
- ~+9 hours – RPV lower head failure
- ~+12 – 23.5 hours – leak through DW head flange
- ~+ 23.5 hours – Wetwell venting
- March 12 – 15:36 – Explosion in Reactor Building

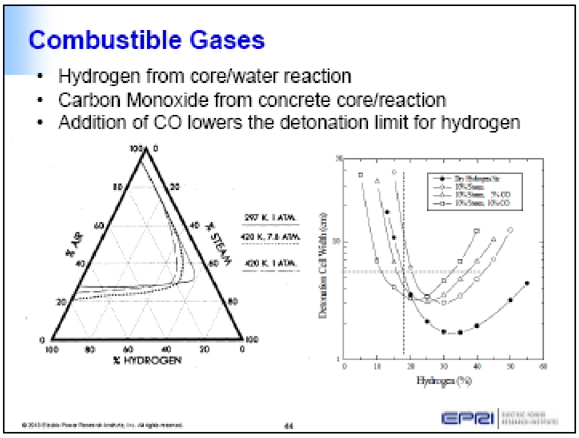

Drywell Pressure Response – MAAP Simulation
Drywell head lifting
Simulation
Measurement
RPV lower head failure
First core relocation into lower plenum
Drywell Pressure [kPa]
Time [hr]

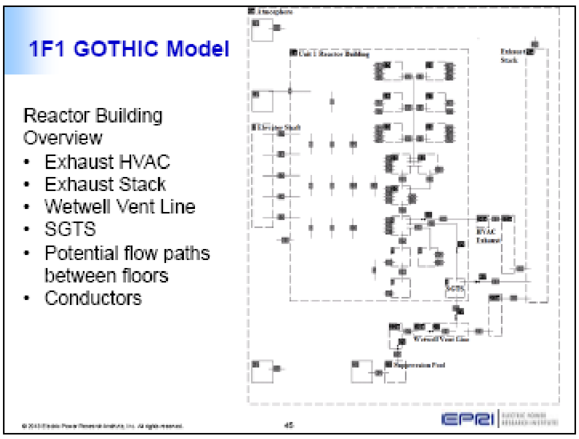

Drywell Release Rate – MAAP Simulation
Drywell Release Rate

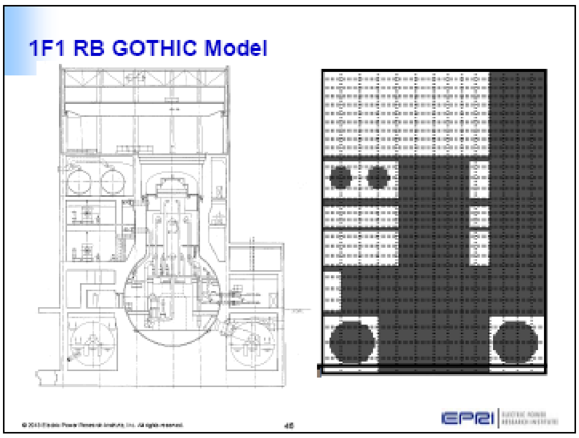

Drywell Gas Concentration – MAAP Simulation
Drywell Concentration
Steam
N2
CO
H2

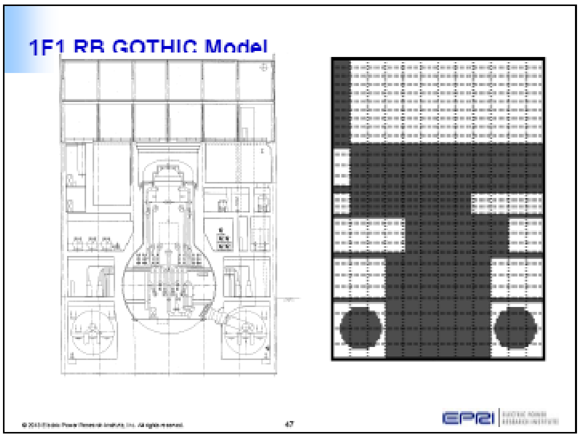

Wetwell Release Rate – MAAP Simulation
Wetwell Release

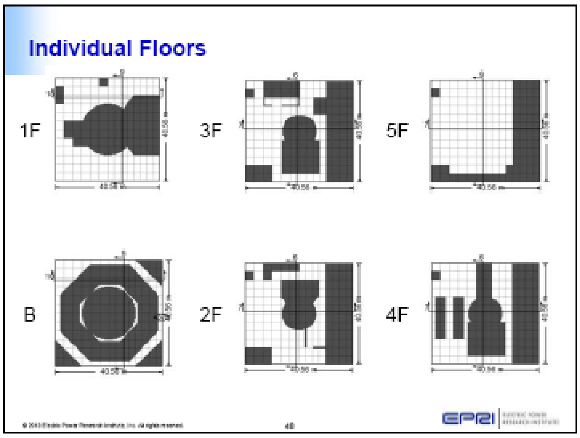

Wetwell Gas Concentrations – MAAP Simulation
Wetwell Concentration
Steam
H2
N2
CO

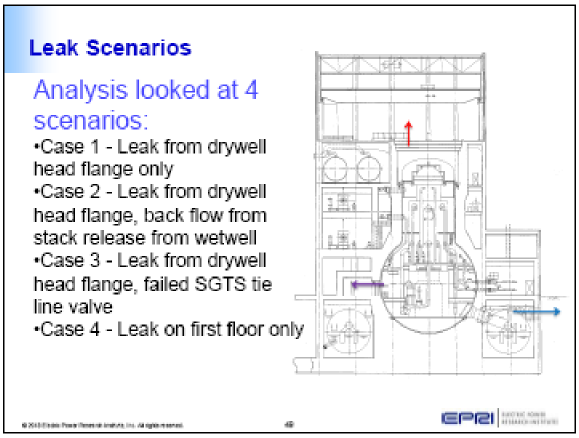

Combustible Gases
• Hydrogen from core/water reaction
• Carbon Monoxide from concrete core/reaction
• Addition of CO lowers the detonation limit for hydrogen
% AIR
% STEAM
% HYDROGEN
297 K, 1 ATM.
420 K, 7.8 ATM.
420 K, 1 ATM.
Detonation Cell Width (cm)
Hydrogen (%)

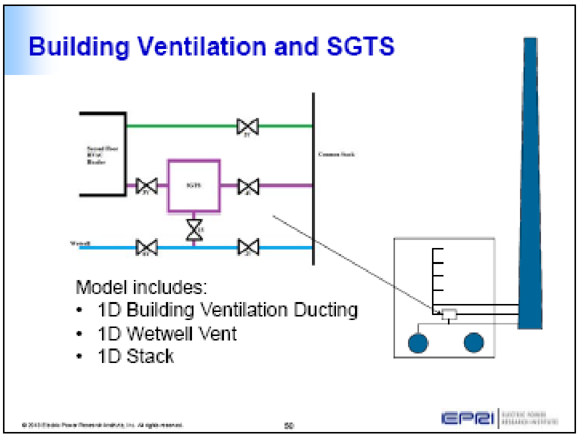

1F1 GOTHIC Model
Reactor Building Overview
• Exhaust HVAC
• Exhaust Stack
• Wetwell Vent Line
• SGTS
• Potential flow paths between floors
• Conductors

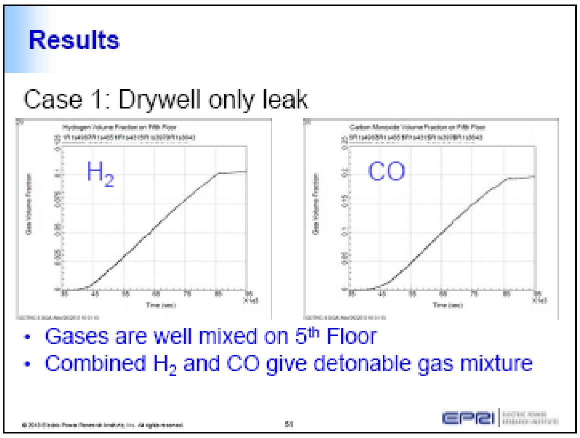

1F1 RB GOTHIC Model

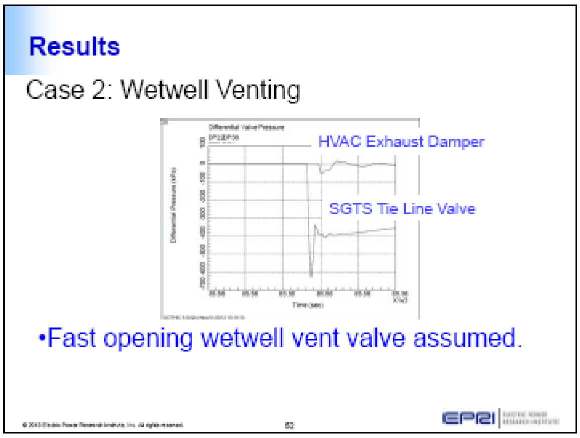

1F1 RB GOTHIC Model
47

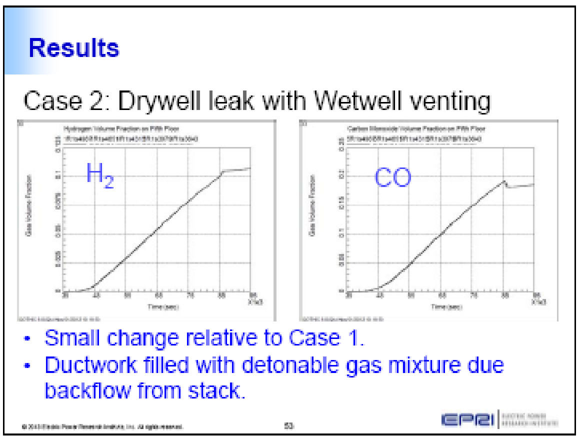

Individual Floors
1F
3F
5F
B
2F
4F
48

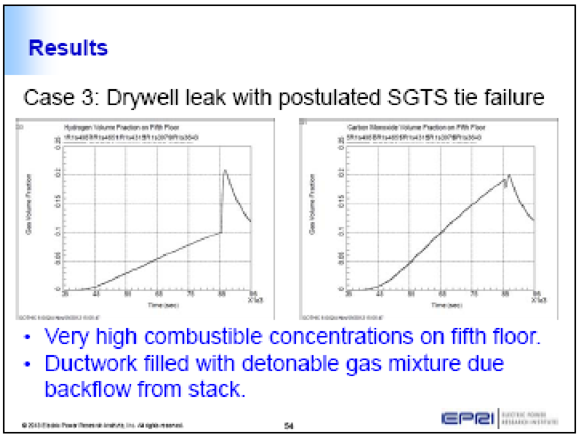

Leak Scenarios
Analysis looked at 4 scenarios:
•Case 1 - Leak from drywell head flange only
•Case 2 - Leak from drywell head flange, back flow from stack release from wetwell
•Case 3 - Leak from drywell head flange, failed SGTS tie line valve
•Case 4 - Leak on first floor only
49


Building Ventilation and SGTS
Model includes:
• 1D Building Ventilation Ducting
• 1D Wetwell Vent
• 1D Stack
50


Results
Case 1: Drywell only leak
H2
CO
• Gases are well mixed on 5th Floor
• Combined H2 and CO give detonable gas mixture
51

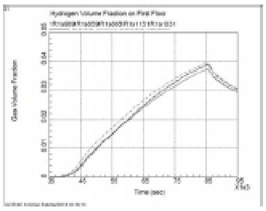

Results
Case 2: Wetwell Venting
HVAC Exhaust Damper
SGTS Tie Line Valve
•Fast opening wetwell vent valve assumed.
52

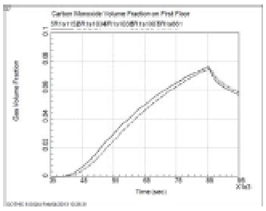

Results
Case 2: Drywell leak with Wetwell venting
H2
CO
• Small change relative to Case 1.
• Ductwork filled with detonable gas mixture due backflow from stack.
53


Results
Case 3: Drywell leak with postulated SGTS tie failure
• Very high combustible concentrations on fifth floor.
• Ductwork filled with detonable gas mixture due backflow from stack.
54

Results

Case 4: First floor leak only





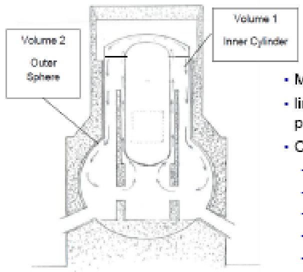
- Combustible (not detonable) gas mixtures throughout the building

Conclusions

- Case 1 provides enough H_2 and CO for detonation.
- Case 2 shows backflow has a minimal effect on 5th floor concentrations but supplies detonable mixture in HVAC.
- Case 3 is unlikely as the entire building contained a highly reactive mixture throughout the building.
- Case 4 shows a release on lower floors gives thoroughly mixed combustible gas throughout the building.

Comments – Questions ?

Drywell Mixing – 1F1 Simulation

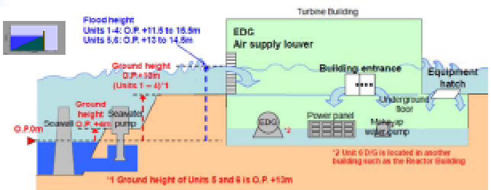


- Model based on
- limited information for actual plant.
- Conductors included for:
  - RPV
  - Steam and recirculation piping
  - DW liner/gap/concrete
  - Vent Ring Header
  - Vents

Significant Observations
Drywell Performance

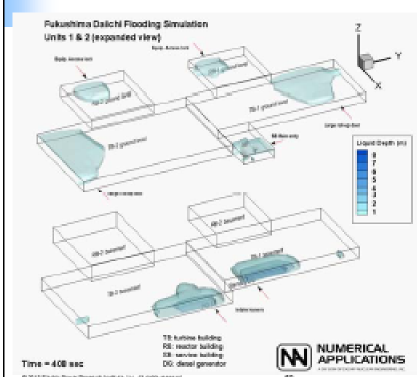
- Based on Unit 1 Simulation
  - Significant vertical temperature variation
  - Temperature at flange location supports flange leakage
  - Hydrogen concentration is nearly uniform
  - Sensitivity studies indicate that wetwell performance could significantly affect containment pressure and therefore scenario assumptions
    - Vent heat transfer
    - Pool stratification
    - Ongoing investigations to quantify these effects

1F1/1F2 Flooding



- Model includes basement and ground floor level of Units 1 and 2 and surrounding water basin to simulate the tsunami surge and fall.
- Model based on limited information on door and penetration leakage.

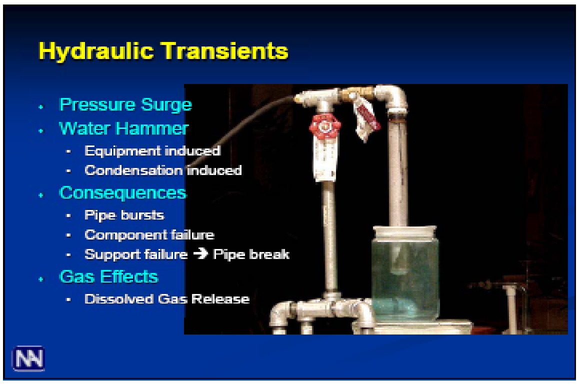
Flooding Simulation

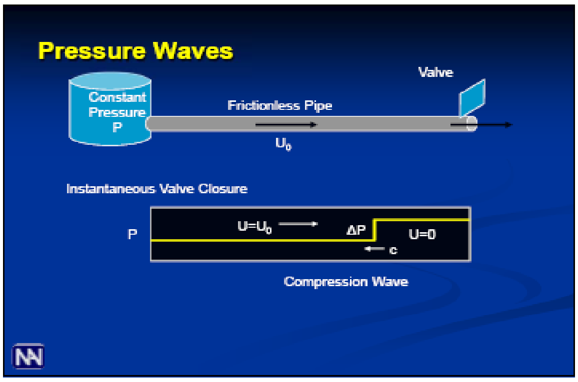


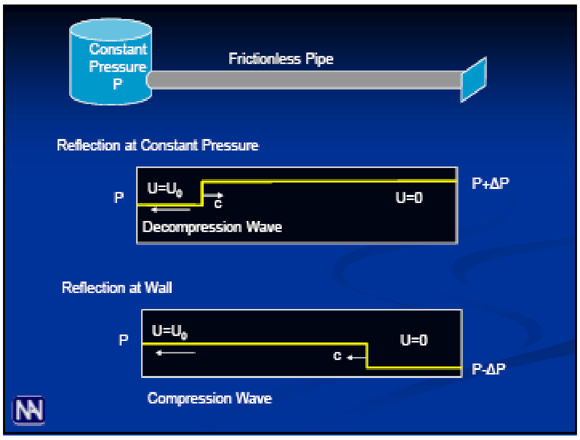
Significant Observations
Tsunami Flooding

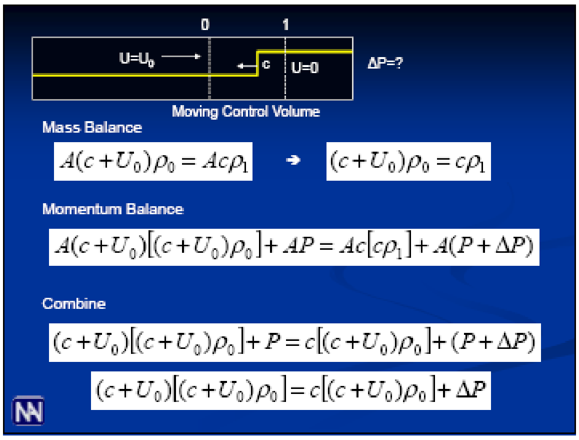
- Based on Units 1/2 Simulation
  - Minimal data available for predictive performance and benchmarking.
  - Flooding path for torus room is not clear but can be simulated under various assumptions.
  - This analysis is largely a demonstration of GOTHIC capabilities for flooding analysis.

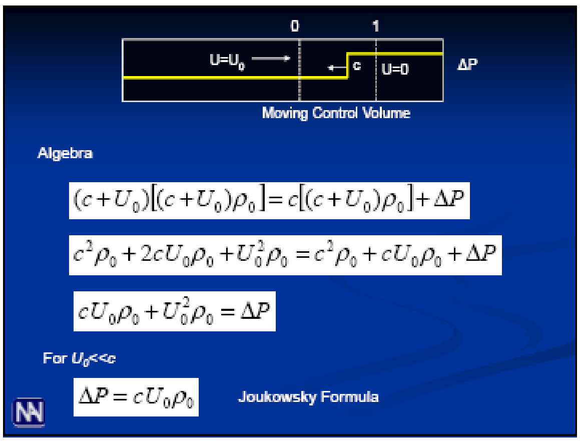
(四) NAI 提供之水槌與 AP load 分析之簡介

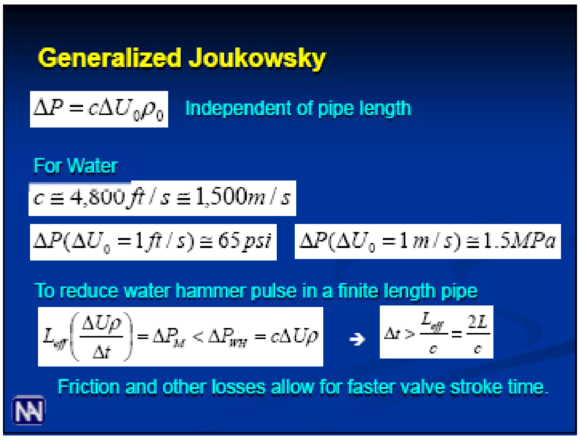


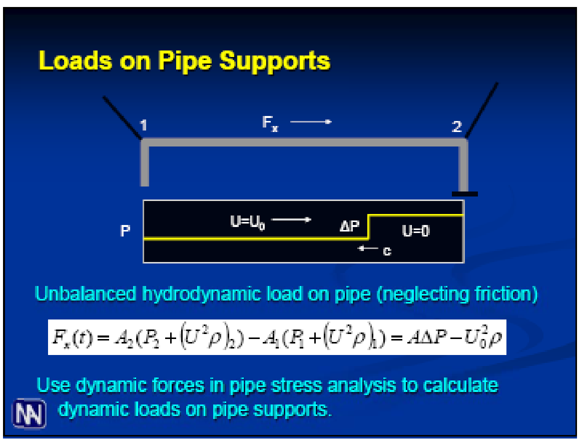


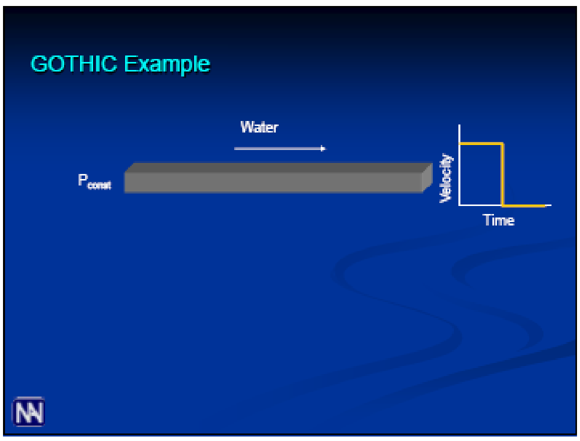




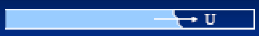








Water Hammer Modeling – GOTHIC 8.0



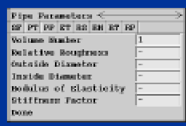
$\Delta P = \rho U c_{eff}$

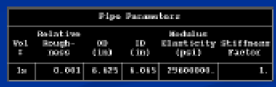
- Effective sonic velocity, c_{eff} – depends on
  - Water compressibility
  - Bubbles in water
  - Pipe properties and support
- Testing
  - Effects of pipe elasticity on wave speed
  - Pressure Pulse from valve closure
  - Water hammer in a simulated fan cooler
  - Water hammer due to column separation with surge tank mitigation
  - Effects of noncondensing gases on wave speed

Water Hammer Modeling

- Wave speed for fluid in Elastic Pipe

$$c = \sqrt{\frac{K/\rho}{1+(K/E)(D/t)\lambda_s}}$$





- System Stiffness – depends on
  - Poisson's Ratio
  - Pipe anchoring
  - Thin vs. Thick wall
  - Material Response Time

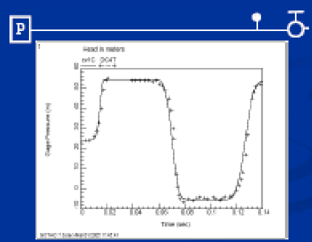
Water Hammer Testing - Wave Speed

- Pipe Elasticity
- 100 ft, ¾ inch, pipe with 2 ft nodes
- GOTHIC Speed Calculated over a 10 ft length
- Stiffness factor = 1.0

Pipe Material	GOTHIC Wave Speed (ft/s)	Theoretical Wave Speed (ft/s)
Rigid pipe	4840	4897
Copper pipe	4256	4224
Plastic pipe	1408	1362

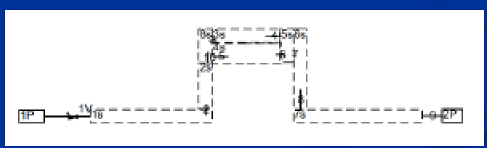
Water Hammer Testing - Pressure Pulse

- 100 ft, ¾ inch, Cu pipe with 2 ft nodes, Input stiffness factor = 2.0
- Liquid speed at time of downstream valve closure = 0.784 ft/s
- Valve closure time = 17ms
- U of Michigan data from Wylie & Streeter



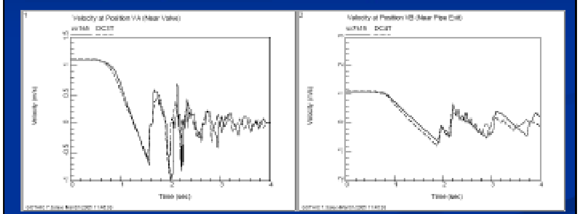
Water Hammer Testing - Delft Hydraulics Laboratory Test 180

- 40 m horizontal span, 90 mm Plexiglas pipe with 1m nodes
- 2m simulated condenser, 20 mm Plexiglas tubes with 0.33 m nodes
- Input stiffness factor = 2.0
- Liquid speed at time of upstream valve closure = 1.1 m/s
- Valve closure time = 1 s



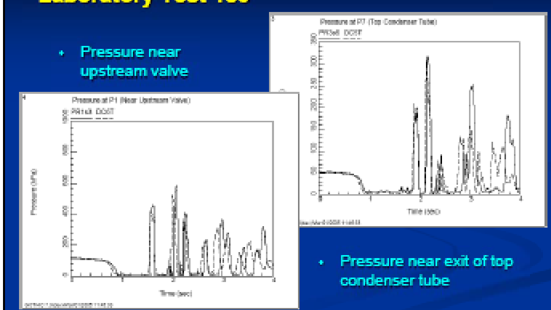
Water Hammer Testing - Delft Hydraulics Laboratory Test 180

- Velocity near upstream valve
- Velocity near downstream exit



Water Hammer Testing - Delft Hydraulics Laboratory Test 180

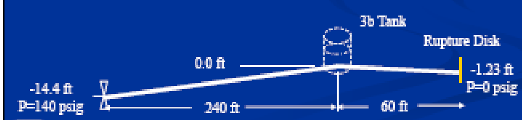
- Pressure near upstream valve

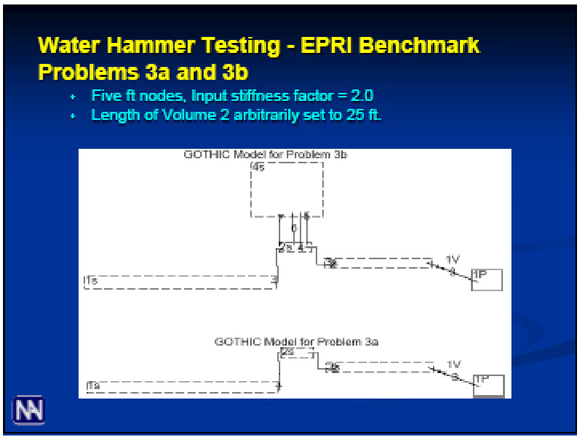


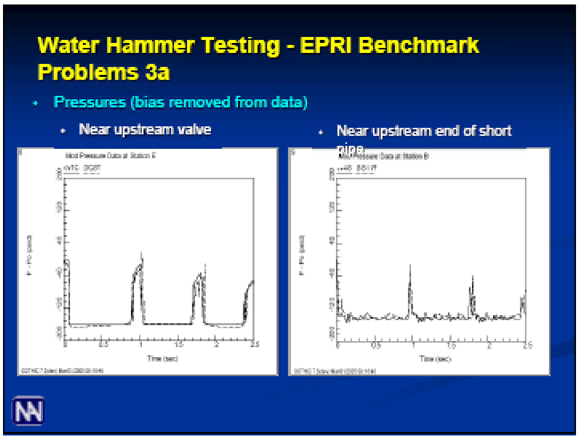
- Pressure near exit of top condenser tube

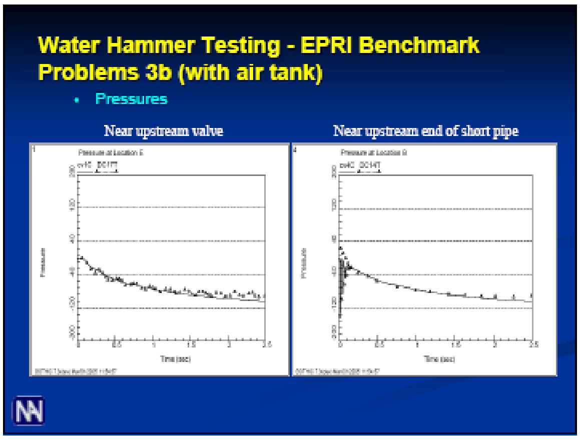
Water Hammer Testing - EPRI Benchmark Problems 3a and 3b

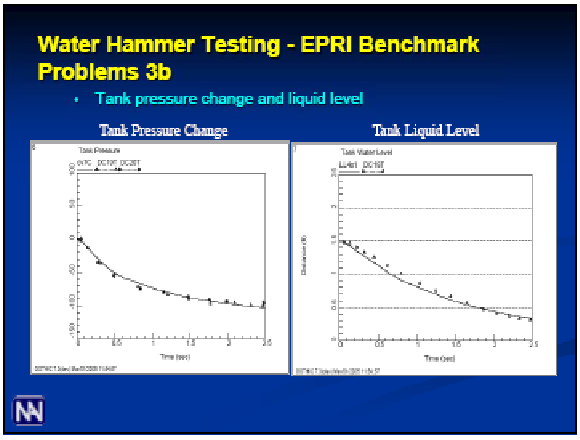
- 8" I.D. sloped steel pipe
- Upstream valve closes instantly with rupture of downstream disk
- Problem 3a as shown without tank
- Problem 3b has air tank inserted at junction of long and short pipes
- Air tank is 44 in high by 31.25" diameter, contains 30" water

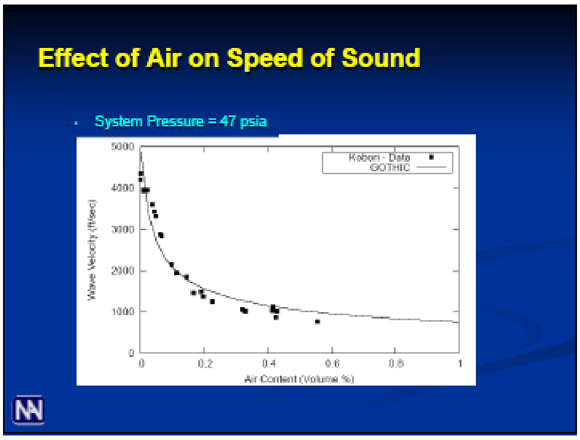


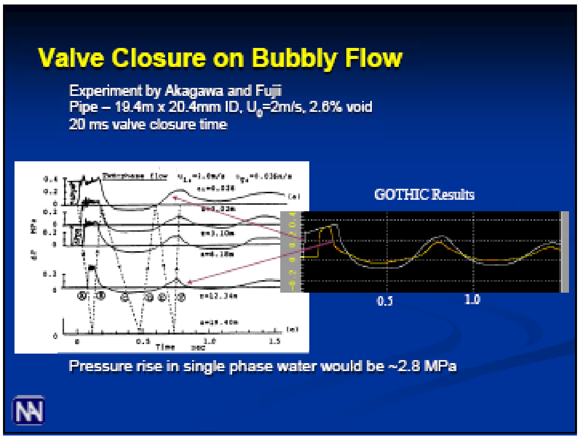

Water Hammer Testing - EPRI Benchmark Problems 3a and 3b
Five ft nodes, Input stiffness factor = 2.0
Length of Volume 2 arbitrarily set to 25 ft.
GOTHIC Model for Problem 3b
GOTHIC Model for Problem 3a

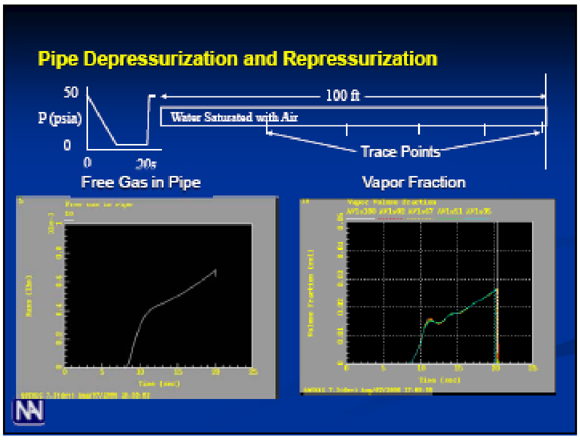

Water Hammer Testing - EPRI Benchmark Problems 3a
Pressures (bias removed from data)
Near upstream valve
Near upstream end of short pipe

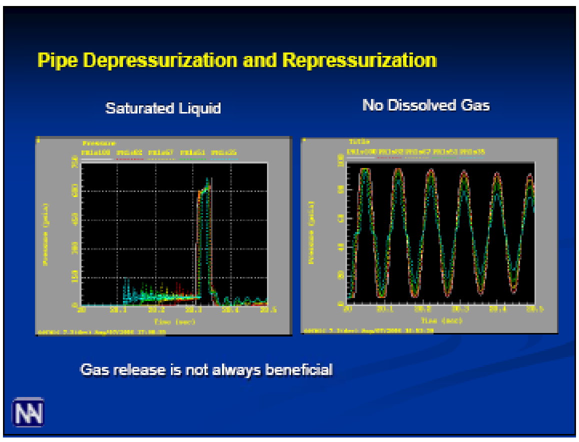

Water Hammer Testing - EPRI Benchmark Problems 3b (with air tank)
Pressures
Near upstream valve
Near upstream end of short pipe


Water Hammer Testing - EPRI Benchmark Problems 3b
Tank pressure change and liquid level
Tank Pressure Change
Tank Liquid Level

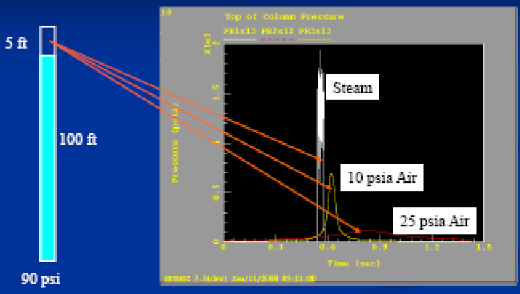

Effect of Air on Speed of Sound
System Pressure = 47 psia
Kobori - Data
GOTHIC
Wave Velocity (ft/sec)
Air Content (Volume %)


Valve Closure on Bubbly Flow
Experiment by Akagawa and Fujii
Pipe – 19.4m x 20.4mm ID, U0=2m/s, 2.6% void
20 ms valve closure time
GOTHIC Results
Pressure rise in single phase water would be ~2.8 MPa


Pipe Depressurization and Repressurization
50
P (psia)
0
0
20s
100 ft
Water Saturated with Air
Trace Points
Free Gas in Pipe
Vapor Fraction


Pipe Depressurization and Repressurization
Saturated Liquid
No Dissolved Gas
Gas release is not always beneficial

Air vs Steam Filled Voids



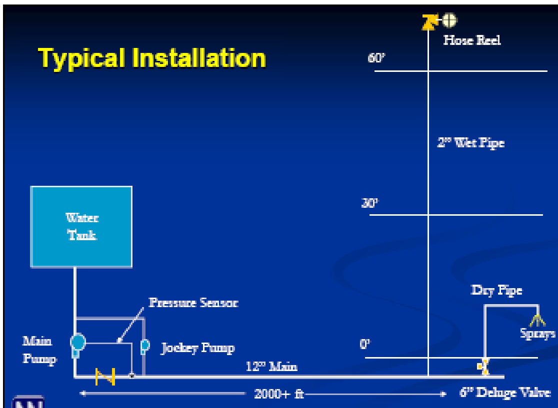
Examples

- Fire Suppression System
- BWR Turbine Exhaust
- Check Valve Slam

Waterhammer in Fire Protection Piping Systems

- NRC Information Notice 98-31
  - Waterhammer Event at Columbia Generating Station
  - Opening of a FPS "Pre-action" valve
  - Voiding in tall system risers
  - Waterhammer after startup of main fire pumps
  - Pipe or valve rupture and flooding

Typical Installation



Operation

- Jockey pump maintains system pressure (~100 psia)
- Quick Open Deluge Valve opens on fire detection
- Deluge System fills
- Pressure drops in main piping
- Main fire pump start on low pressure signal
  - Electric fire pumps
  - Diesel fire pumps

Void Formation

- Pressure at Hose Reel angle valve

$$P = P_{main} - \rho g H$$

- If $P<P_{sat}(T)$ steam pocket forms at top of riser
- At T=80F and Pmain=1atm
  void forms if H>33'

Void Formation

- Size of void depends on
  - H
  - Fluid inertia and drag in the riser
  - Time that low pressure persists in the main piping
    - Expansion wave may take 0.5s or more to reach the pressure sensor
    - Delay in pump start up, especially diesel driven pumps
    - Compression wave may take 0.5s or more to return to the bottom of the riser
    - Fill time for the spray system

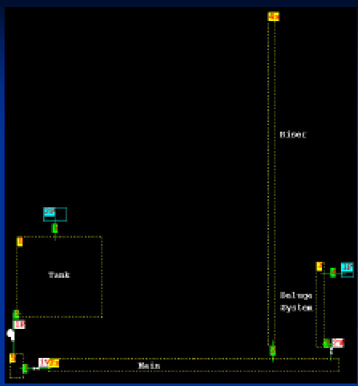
Void Collapse and Waterhammer

- Void collapses as main pressure is restored
- Waterhammer pressure pulse is given by Joukowsky formula

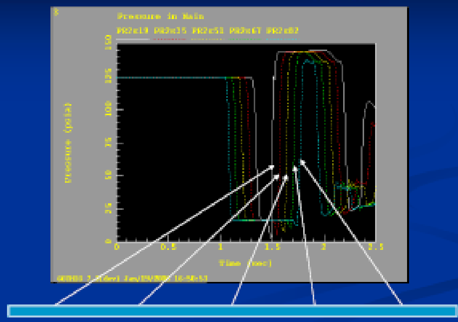
$$\Delta P = a\rho U$$

  - a – speed of sound = ~4,900 ft/s
  - U – closure velocity
- At U=10 ft/s, ΔP = 655 psi
- U depends on
  - Size of void
  - Pressure restoration rate
  - Inertia and drag in the riser

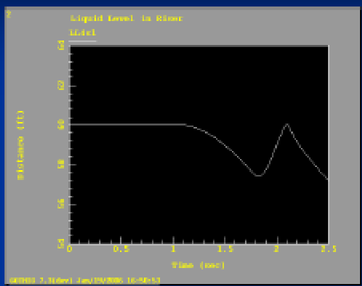
GOTHIC Model for Simple System



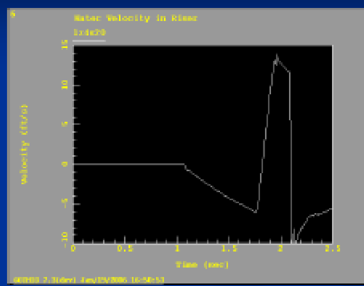
Pressure Transient in Main Piping



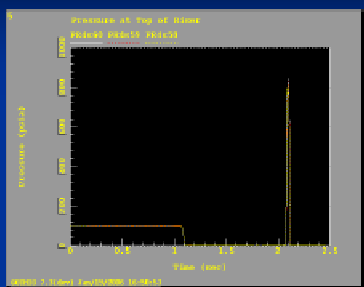
Liquid Level in Riser



Velocity in Riser



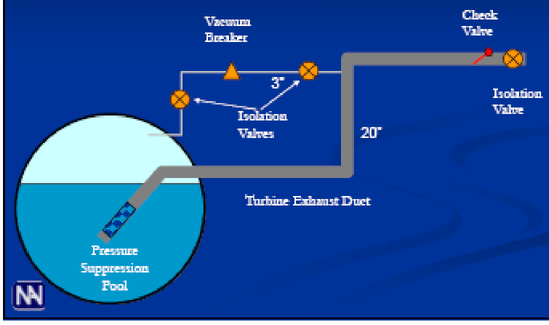
Pressure at Top of Riser



Possible Remedies

- Check valves in risers
- Pressurized accumulator tank near risers
- Vacuum breakers at top of risers and inverted U's in elevated piping
- Controlled start of flow from the fire pump

Pressure Surge BWR RCIC and HPCI Turbine Exhaust Isolation



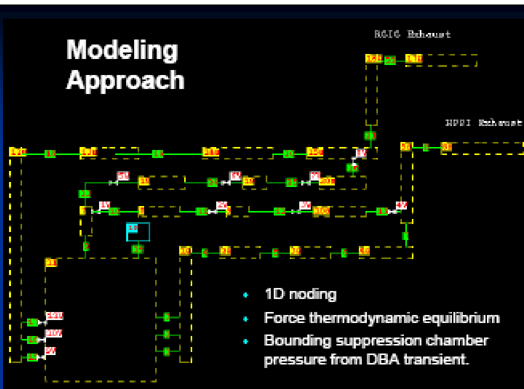
Transient Conditions

- Quick closing isolation valve on turbine trip on low RPV pressure signal.
- Vacuum Line isolation valve begins to just after the turbine trip.
  - Stroke time > 10 seconds
- Pressure quickly drops in the exhaust pipe when the steam condenses.
- Water fills the exhaust pipe from the suppression pool
- Air enters the exhaust pipe via the vacuum line.

Concerns

- Pressure pulse when exhaust pipe fills with water.
- Dynamic loads on exhaust pipe supports.
- Pressure pulse at the vacuum breaker.
- Dynamic loads on vacuum lines.

Modeling Approach

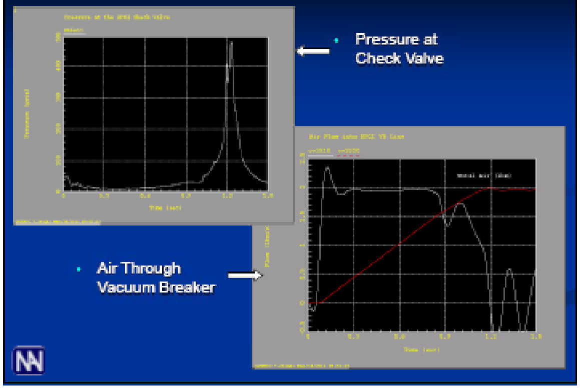


- 1D noding
- Force thermodynamic equilibrium
- Bounding suppression chamber pressure from DBA transient.

Piping Loads

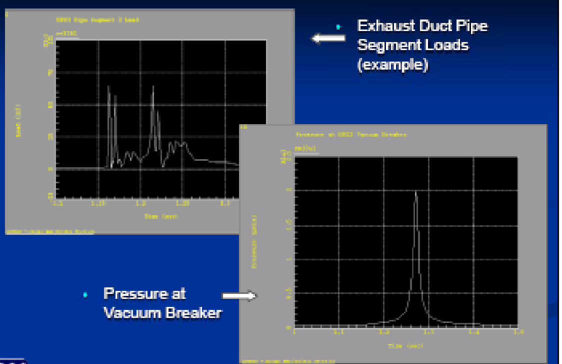
- Control Variables configured to capture dynamic load on each pipe segment, including
  - End static pressure loads
    PA
  - End momentum loads
    $A\alpha_l\rho_l u_l^2$
  - Wall drag (approximate)
  - Deduct fluid weight (vertical runs) (accounted for in piping support loads analysis).

HPCI Turbine Exhaust Pressure Transient



- Pressure at Check Valve
- Air Through Vacuum Breaker

HPCI Turbine Exhaust Pressure Transient

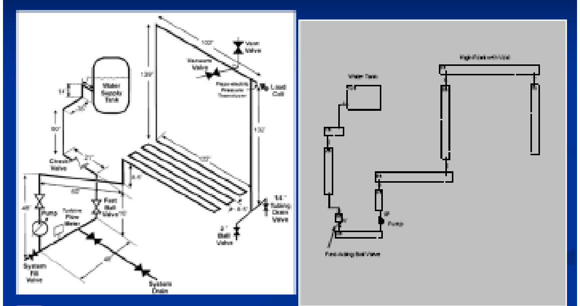


- Exhaust Duct Pipe Segment Loads (example)
- Pressure at Vacuum Breaker

Pressure Surge and Check Valve Slam

- FAI Tests for
  - Pressure surge in pump discharge line due to trapped air
  - Water hammer due to check valve slam upstream of the pump
- Analytic investigations
  - Check valve location relative to the pump
  - Check valve distance from pipe end

FAI Test Setup / GOTHIC Model



Important Assumptions

- One dimensional
- Built-in GOTHIC pump curves; pump ramps up linearly
- Size of water tank was estimated (3x3x5)
- Pump was started 0.5 seconds after valve was opened
- Ball valve was modeled as opening instantaneously (instead of 100ms)
- System given 5 seconds to settle out

First Runs

- Found that some of the test physics were missing in the model.
- Changed water tank size
- Changed pump start time
- Modified subdivided volume noding.
  - Smaller noding = more refined data
  - 1 ft mostly, 0.5 ft near void
- Switched from quick close valve to vacuum breaker.
  - Vacuum breakers solve angular momentum equation.

Vacuum Breaker

- Moment of inertia
  - Estimated from drawing
- Damping coefficient
  - Taken from Blevins ("Applied Fluid Dynamics Handbook")
- Hinge friction
  - Estimated from closure time
- Vacuum breaker mass
  - Estimated from drawing
- Opening angle
  - Estimated from drawing

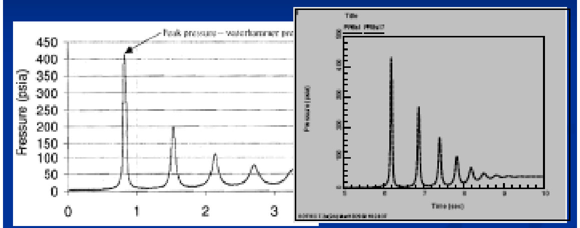
Investigations

- Match case with no check valve
- Match case with upstream check valve
- Model check valve downstream of pump
- Add 300 ft piping between valve and pump
- Add 300 ft piping after valve
- Check valve located next to void
- Upstream check valve with 300 ft added between tank and valve

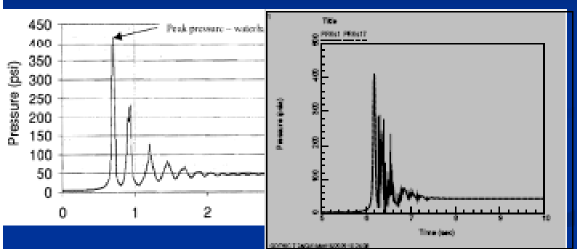
Observations

- Two pressure waves
  - Big rolling waves from void compression
  - Fast shock waves from valve slam
- Axial loads calculated from pressure differential in pipe with void
- Test equipment not fast enough to pick up all events
- Test pipes were flexible, not secured and load sensor measure pipe motion

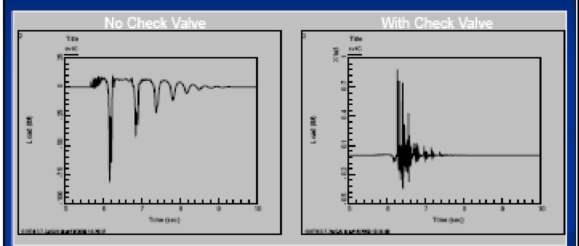
Pressure Results with No CV



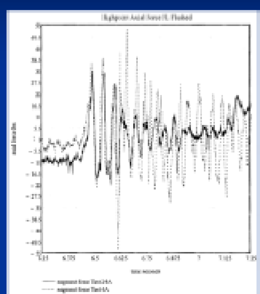
Pressure Results with CV



Axial Loads for End Pipe Segment



FAI Axial Loads

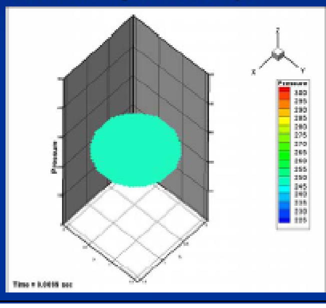


Conclusions

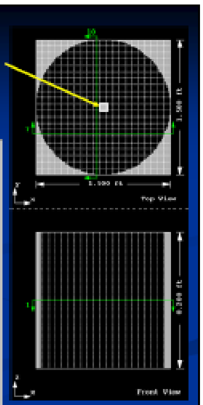
- Valve placement, pipe lengths, valve parameters, and event time schedule add to the unique frequency of the system
- Vacuum breaker effective for modeling check valve but results are sensitive to uncertain input parameters
- Valve slam pressure pulse increase with increase water slug length

Multidimensional Hydrodynamic Transients

Variable Porosity Tube Collapse



Tube

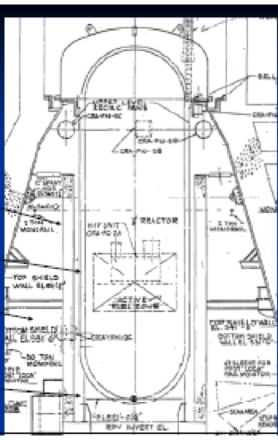


Annulus Pressure Transient For Recirculation Water Line Break

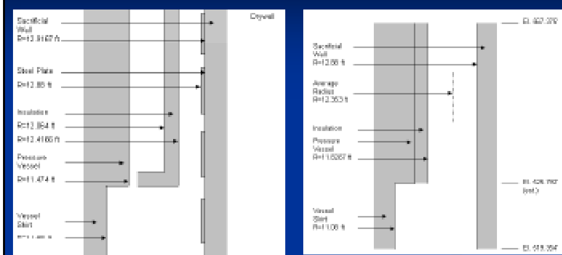
Objective

- Estimate dynamic loading on the reactor pressure vessel due to a line break inside the annulus
- Retain previous modeling assumption as possible

Mark II Geometry



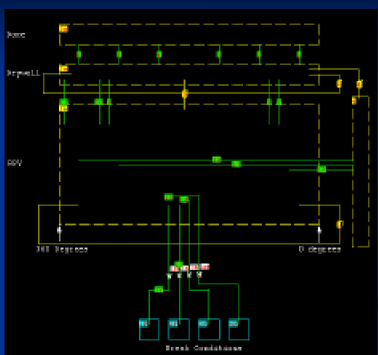
Annulus Geometry



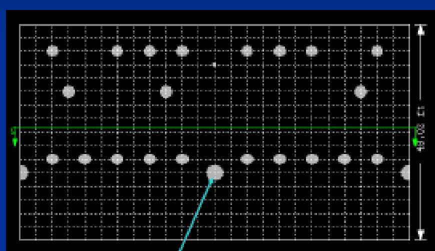
Actual

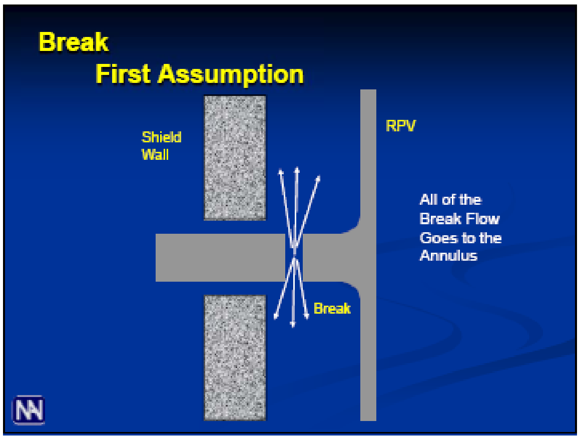
As Modeled

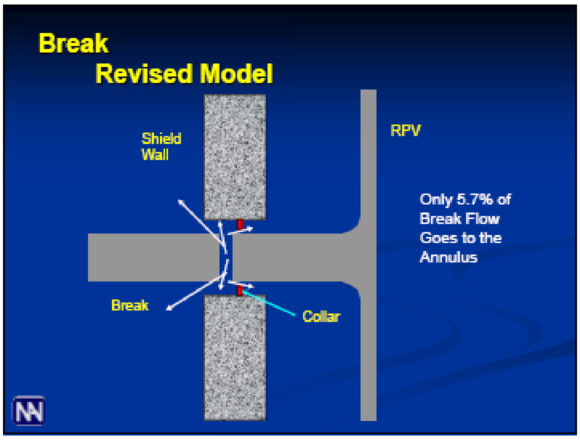
Drywell/Annulus Model

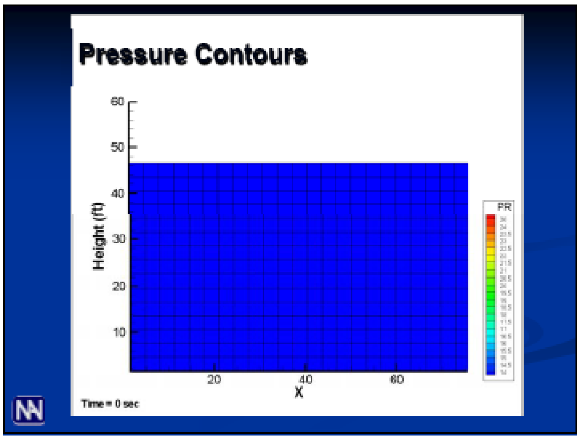


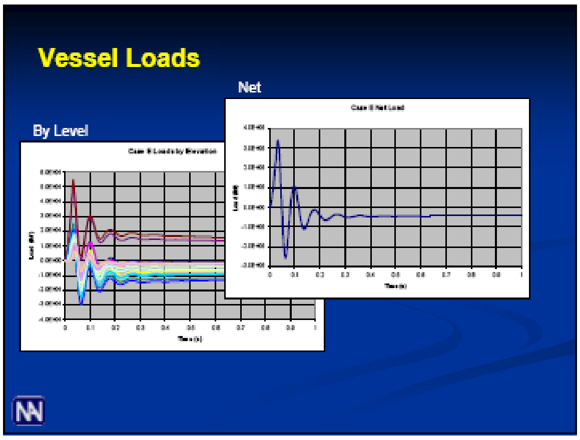
2D Annulus Model

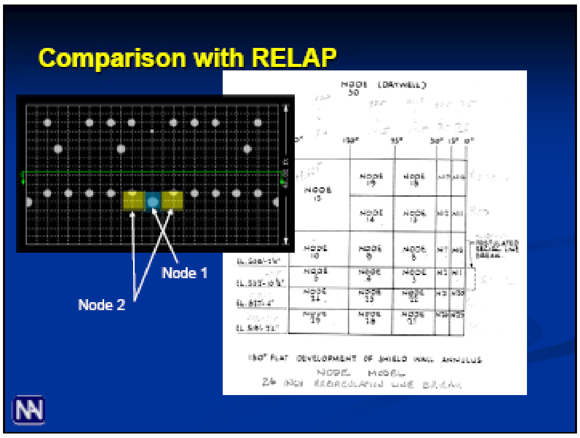


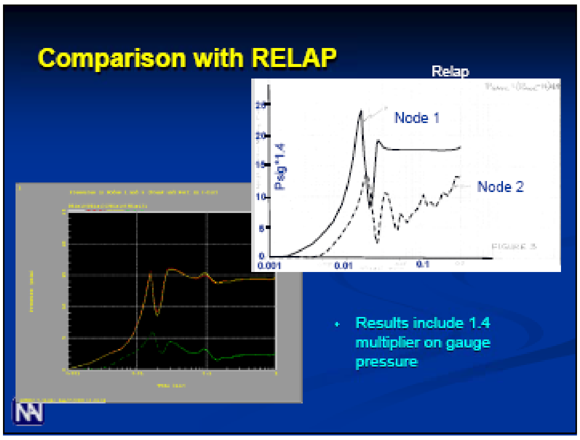

Break
First Assumption
Shield
Wall
RPV
All of the
Break Flow
Goes to the
Annulus
Break

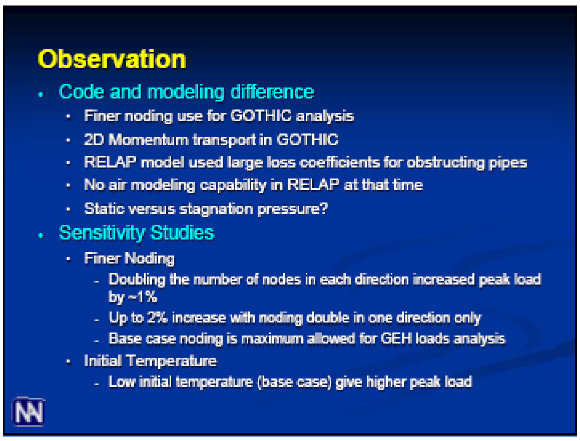

Break
Revised Model
Shield
Wall
RPV
Only 5.7% of
Break Flow
Goes to the
Annulus
Break
Collar


Pressure Contours
Height (ft)
X
PR
Time = 0 sec


Vessel Loads
Net
By Level


Comparison with RELAP
Node 1
Node 2


Comparison with RELAP
Relap
Node 1
Node 2
Psig*1.4
Results include 1.4
multiplier on gauge
pressure


Observation
Code and modeling difference
Finer noding use for GOTHIC analysis
2D Momentum transport in GOTHIC
RELAP model used large loss coefficients for obstructing pipes
No air modeling capability in RELAP at that time
Static versus stagnation pressure?
Sensitivity Studies
Finer Noding
Doubling the number of nodes in each direction increased peak load by ~1%
Up to 2% increase with noding double in one direction only
Base case noding is maximum allowed for GEH loads analysis
Initial Temperature
Low initial temperature (base case) give higher peak load

(五)與 NAI 未來之合作項目規畫

以下內容由 NAI 負責人 Dr. Tom George 於 7 月 27 日寄送給本所苑穎瑞博士。

From: George, Thomas L. [mailto:tom.george@numerical.com]
Sent: Saturday, July 27, 2013 12:18 AM
To: 苑穎瑞
Cc: Carstens, Nathan A.
Subject: FW: GOTHIC Budgetary Estimates for INER

Dear Dr. Yuann,

We are pleased to provide a rough budgetary estimate for the tasks we recently discussed. This will give you some idea of the level of effort required for these tasks. The actual cost would depend on the details of the scope to meet your requirements.

We look forward to any feedback and would be happy to provide more detail or even a formal proposal when you are ready.

Year 1:

Task 1: PAR Modeling:

a) Build a 3D containment model of a PWR. This model should account for the major thermal hydraulic phenomena that will be present during a station blackout (SBO) condition. This includes a three dimensional model (individual rooms may be modeled as lumped volumes) capturing room layout including significant free versus obstructed spaces and significant thermal conductors that may exchange heat with the atmosphere over a several hour time frame. Provide quality assured documentation of the containment model. INER would provide drawings and other documents sufficient to build the 3D GOTHIC model for the containment (the HVAC will not be modeled as it will not be active during an SB).
b) Build a simple primary system model and simulate the blowdown of the primary system through the pressurizer PORV. Infinite reactor operation and standard ANS decay curves will be used to model the decay heat. Starting at the time of core uncover, hydrogen will be released to the containment. The amount and duration of the hydrogen released will be based on an assumed 100% oxidation of the fuel cladding and an estimated time for the core to completely uncover.
c) Build and calibrate a PAR model with a quality assured documentation. INER would provide performance specification or test data for a selected recombiner.
d) Use the containment, primary release, and PAR models to perform a single sensitivity study on appropriate location of the PAR's with quality assured documentation.

Task 2: Annulus Pressure:

a) Construct and run and document a GOTHIC model to estimate the mass and energy release into the annulus for either a feedwater or recirculation line break (INER's option). INER would provide the conditions of the primary system, break location, geometry details of the pipe penetration through the shield wall, including details on any flow diverter that would affect the break flow into the annulus. Estimated cost $20k.

b) Construct and run a 2D GOTHIC model for annulus using the break conditions from a). INER would provide detailed drawings for the annulus region, including installed insulation, obstructions due to vessel piping, and support structure and openings into the annulus region.

Task 3: Technology Transfer with either item a or b:

a) Host INER guests in the NAI office in Richland, WA and provide a presentation, question and answer, and demonstration runs with the PAR and AP models. This is estimated to take 3 days of NAI engineer time.

b) Have INER host an NAI engineer in Longtan.

Year 2:

Task 4: Gas Transport:

a) Build a multidimensional GOTHIC piping model of a single water transport system (e.g. RWST tanks to spray system) and provide a quality assured documentation of the model. This model would include the pumps and valves as required to simulate the gas transport. INER would provide isometric drawings for the piping system and performance date for pumps and valves. For this estimate it is assumed that the modeled piping system has no more than 40 piping segments.

b) Execute model for a specified transient (e.g., pump startup) and document the resulting void fraction in the pump.

Task 5: Spent Fuel Pool Model:

a) Build a 3D model for a complete PWR spent fuel pool. The plan grid for the model would combine approximately 40 fuel assembly channels into a single cell. The model will include heat structures for the fuel assemblies, assembly channels, walls and floors of the pool. The pool cooling system will be modeled. The region above the pool will be model to a level sufficient to capture the performance of the building ventilation system. INER will provide the operating history and location of each bundle in the fuel pool. The model will the documented under NAI QA requirements.

b) Run and document simulations using the 3D model for local heating effects. Possible scenarios may include checkerboard patterns and hot core offloading. These models will not consider severe accident scenarios but will estimate local heating and cooling effects for normal operation.

c) Build a detailed version of a small, selected region of the fuel pool to investigate time to run away fuel oxidation. This effort would include a DLL program to simulate the hydrogen generation using the Arrhenius reaction model with local conditions, accounting for the buildup of an oxidized layer on the cladding. Document the model to NAI QA standards.

d) Run and document simulations using the detailed model for selected scenarios (e.g., pool level at various elevations, air only cooling, and sprays).

Task 6: Technology Transfer with either item a or b:

a) Host INER guests in the NAI office in Richland, WA and provide a presentation, question and answer, and demonstration runs with the gas transport and spent fuel pool models. This is estimated to take 3 days of NAI engineer time.

b) Have INER host an NAI engineer in Longtan..

These items would be completed as part of the NAI quality assurance program which conforms to 10CFR Appendix B and ASME NQA-1.

(六)台電公司審查意見與回覆

Comments on the KS2C23 SPU

Preliminary Licensing Reports

1 RLA(ANP-3190(P) Preliminary Rev.0)：

1.1 Section 1.1 (Page1-2)：
Because one KS2R22 A10-4041B-15GV75 new fuel is replaced by KS1R23 A10-4040B-15GV65 new fuel, please add some descriptions about the replacement and the relative impacts.

Response:

The following will be added to Section 1.1:
"Kuosheng Unit 2 Cycle 23 core loading was revised from the original core loading pattern documented in Reference 58 to replace a fresh fuel assembly that was discovered to be damaged during the new fuel inspection. The fuel replacement is given below.

Assembly Name (Fabrication Batch)	Replaced By (Fabrication Batch)	Cycle 23 Core Location
K2H537 (KS2R22)	K1K541 (KS1R23)	15-44

The revised core loading pattern was used in the licensing of Kuosheng Unit 2 Cycle 23 at MUR and SPU conditions therefore there is no impact on the results reported."

1.2 Section 1.3.5 (Page1-5) describes the Region Z for Cycle 23 under SPU conditions increased primarily as a result of the higher SPU power level. Please provide more descriptions about it.

Response:

The slight change in the stability region is primarily due to the more bottom-peaked power shape under SPU conditions. The channel is hydraulically least stable when the power is bottom-peaked and most stable when it is top-peaked.

1.3 Section 1.3.5 (Page1-5)：
Please add the data of power/flow for two decay ratio as before.

Response:

The data will be added to the end of Section 1.3.5:
Compared to MUR conditions, both the lower and upper boundaries of Region Z have increased.

1.4 The core power listed in Table3.1 (Page3-4) is much lower than the value of KS2C23 MUR. Please explain it.

Response:

The safety limit is analyzed for each exposure in the core cycle design step-through. The exposure which calculates the largest number of rods in boiling transition will be used to set the safety limit.

The core power used in each safety limit analysis is raised until the core MCPR value is equal to the safety limit. Because the MUR analyses were performed for the whole of KSH2-23 (i.e. BOC – EOC+500) the limiting exposure for the whole cycle was determined. This limiting exposure was 440 MWd/MTU. However, SPU did not analyze KSH2-23 from BOC. SPU only analyzed cycle exposures of 8,000 MWd/MTU to EOC+500; therefore, a different limiting exposure is determined. This limiting exposure is 10.120 MWd/MTU. Since the core power distribution is different between MUR and SPU and the most limiting exposure is different, their corresponding raised core power is also different.

1.5 The R-value listed in Section 4.2.2 (Page4-2) is lower than the value of KS2C23 MUR, but the loading patterns are the same. Please explain it.

Response:

R is defined as the difference between the BOC calculated shutdown margin and the minimum calculated shutdown margin in the cycle. For SPU conditions, the BOC shutdown margin was calculated at 8,000 MWd/MTU where SPU implementation is expected.

1.6 Because the transient of load rejection with no bypass is analyzed, please add a new section to describe the analysis results.

Response:

Section 1.3.4 of the RLA indicates the LRNB transient has been added for SPU. A detailed description of the LRNB transient and results is provided in in Section 5.1.2.3.

1.7 The fuel/clad gap conductance lasted in page5-12 are much lower than the values of KS2C23 MUR, please provide descriptions about it.

Response:

The fuel/clad gap conductance is a function of power history and core power level. For the SPU analyses, the core follow data has been updated to include the whole of KSH2-22 and part of KSH2-23 compared to the KSH2-23 MUR HGAP analyses which used core follow for only part of

KSH2-22 and then a project for the remainder of KSH2-22 and all of KSH2-23. This difference in restart files means the power history data used in the HGAP calculations is different between the MUR and SPU calculations. The core power level is also different between MUR and SPU conditions. The difference in the HGAP values is only on the order of 2-3% and is an expected and reasonable difference based upon the differences in the power histories.

1.8 Page5-14：The FWCFNB transients at 40% power and below without RPT have not been analyzed from KS1C20. Why are these transients analyzed for KS2C23 SPU?

Response:

The additional FWCFNB events are used to verify that the TTNB events remain to be the limiting cases for 40% power and below under the SPU conditions. Based on the results shown in the RLA, the FWCFNB event will not be analyzed below 40% power in future cycles.

1.9 Page5-15：The steam lines pressure for MSIV closure transient is much lower than the value of KS2C23 MUR, and the steam lines pressure for TCV closure transient is much higher than the value of KS2C23 MUR. Please provide descriptions about the results.

Response:

The calculated pressure results for the MSIV closure are very similar between MUR and SPU and the same is true for TSV closure. There are big differences in the calculated pressure between MUR and SPU for the TCV closure. The big differences in calculated pressure for TCV closure is a result of changes SPU cause in the TCV characteristics. For SPU, the TCV valves are much more open than in the MUR analyses resulting in a longer stroke time to close the valves. This longer stroke time results in lower peak pressures being calculated. Therefore, because of the initial TCV position is different between MUR and SPU conditions, the maximum pressure for both ASME events are changed accordingly.

1.10 Page 6-2：The maximum dropped control rod worth compared with the value of KS2C23 MUR is increased, but the maximum deposited fuel rod enthalpy is decreased. Why are the changes reversed?

Response:

Using the higher SPU maximum dropped control rod worth would likely result in the maximum deposited fuel rod enthalpy very close or exceeding the 280 cal/gm limit. Therefore, the conservatism in the calculation of the maximum local peaking factor was reduced. For MUR conditions, the limiting CRDA case was analyzed using the maximum local peaking factor (LPF) from all enriched zones which is very conservative. For SPU conditions, the limiting CRDA case was narrowed to +/- 5 nodes within the maximum power node. The result of this is a lower LPF being used to calculate MED and therefore a lower MED. This was done to not report an overly conservative result that is close to the limit.

2 Operability Assessment：(12-9196633-000)

2.1 In section 2.0, the MICROBURN-B2 version is changed from ufeb12 to usep12. What are the significant changes?

Response:

During the MUR licensing campaign an error (CR2012-8772) was found in the ufeb12 version that the limiting rod method does not always select the most limiting rod for the MCPR calculation. This was corrected in the usep12 version. There are no other significant changes that affect the operability assessment calculations.

2.2 In Page 7, the value of available margin to $MCPR_f$ limits for cycle exposure between 8.0 and 8.8 is changed from 0.046 to 0.070. Please provide description about the change.

Response:

In the MUR analysis, the minimum MCPRf margin occurs at exposure=4400.0 MWd/MTU. Since SPU exposure started at 8000 MWd/MTU which already pass the limiting exposure, the MCPRf margin is significantly increased.