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出國報告（出國類別：其他）

赴美 Zachry 公司進行 GOTHIC 熱水流分析模式討論工作

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派赴國家：美國
出國期間：106 年 7 月 19 日~106 年 7 月 30 日
報告日期：106 年 8 月 8 日

摘　要

本所核工組於執行台電公司委託之「核二廠終期安全分析報告書對於輔機廠房之事故環境狀況之重估工作」計畫中，與美國 Zachry 公司的 Numerical Application 部門(原為 Numerical Application Inc.)有所合作，本所人員使用該公司發展之 GOTHIC 程式計算廠房在發生高能管路斷管事故時的壓力、溫度、相對溼度的變化，本次公差指派副研究員陳彥旭與研究助理林恩聖二員前往位於美國華盛頓州里其蘭(Richland, WA)的 Zachry 辦公室，目的係請該公司協助改善本所發展之廠房分析模式，並交換 GOTHIC 程式的使用經驗。本所人員與 Zachry 公司就廠房事故分析、用過燃料池、乾式貯存、替代衰變熱移除、Inter Process Communication 等 GOTHIC 程式的功能或應用範圍進行交流，收穫甚多。整體而言，此次出國公差達成既定之目標。

關鍵字：GOTHIC 程式、廠房熱流分析

目　　次

一、目　的

本所核工組接受台電公司核二廠委託之「核二廠終期安全分析報告書對於輔機廠房之事故環境狀況之重估工作」(計畫編號 BNS0382)，該計畫使用 GOTHIC 程式計算輔機廠房廊道與房間在發生高能管路斷管事故時的壓力、溫度、相對溼度的變化。該程式係由 Zachry 公司的 Numerical Application 部門(原為 Numerical Application Inc.)所建立發展，為增進本所人員相關技術能力，精進現有分析模式等有助於計畫執行之工作，指派副研究員陳彥旭與研究助理林恩聖二員前往位於美國華盛頓州里其蘭(Richland, Washington state)的 Zachry 公司的 Numerical Application 部門辦公室，討論相關分析技術與模式，並交換 GOTHIC 程式的使用經驗，工作期間為 7 月 19 日至 30 日。

二、過　程

(一)本次公差行程說明

Zachry 公司的 Numerical Application 部門(簡稱 NAI)於美國華盛頓州的里奇蘭市(Richland, WA)，該市與南邊的 Kennewick 及東邊的 Pasco 合稱為 Tri-cities，機場則位於 Pasco。美國在二戰期間配合曼哈頓計畫，在西北的華盛頓州設置反應器提煉鈽，附近城鎮也因大量工作人員進駐而發展，包括 Richland。

本次公差二員於 7 月 19 日晚上搭機抵達美國西雅圖 Tacoma 機場，再轉機至 Pasco 機場。二員住宿地點 M Hotel 位在 Richland 的 George Washington Way，NAI 辦公室位於附近的 Jadwin Avenue，如圖 1 所示。

NAI 原本是間獨立的公司，本所核工組數年前引進該公司發展的 GOTHIC 程式，該程式在美國核能界已有許多應用，核工組亦將其用於國內電廠的圍阻體分析技術，以支援相關安全分析工作，包括核一廠中幅度功率提昇案等。NAI 數年前被 Zachry 公司併購，成為該公司的一個部門，但在技術上仍維持獨立運作。

本次公差雖然僅在 Richland，但 Zachry 公司仍指派一位在 Cary (North Carolina)辦公室的專家到 Richland 辦公室支援，過程中亦有 Stonington (Connecticut)辦公室的人員藉由視訊方式參與。Cary 與 Stonington 辦公室均位於美國東岸，如圖 2 所示。

到達 NAI 辦公室後，首先由該公司 Kevin Wheelwright 接待，安排辦公室位置及介紹周圍環境。Scott Franz 博士則擔任本次公差人員與該公司連絡之窗口，技術方面則由部門負責人 Tom George 博士以及該公司北卡州 Cary 辦公室到來的 Skip Denny 顧問負責。

本次公差主要討論二議題：一為核二廠輔機廠房設備驗證(Equipment Qualification)分析，另一則為用過燃料池(Spent Fuel Pool)熱流分析模式。

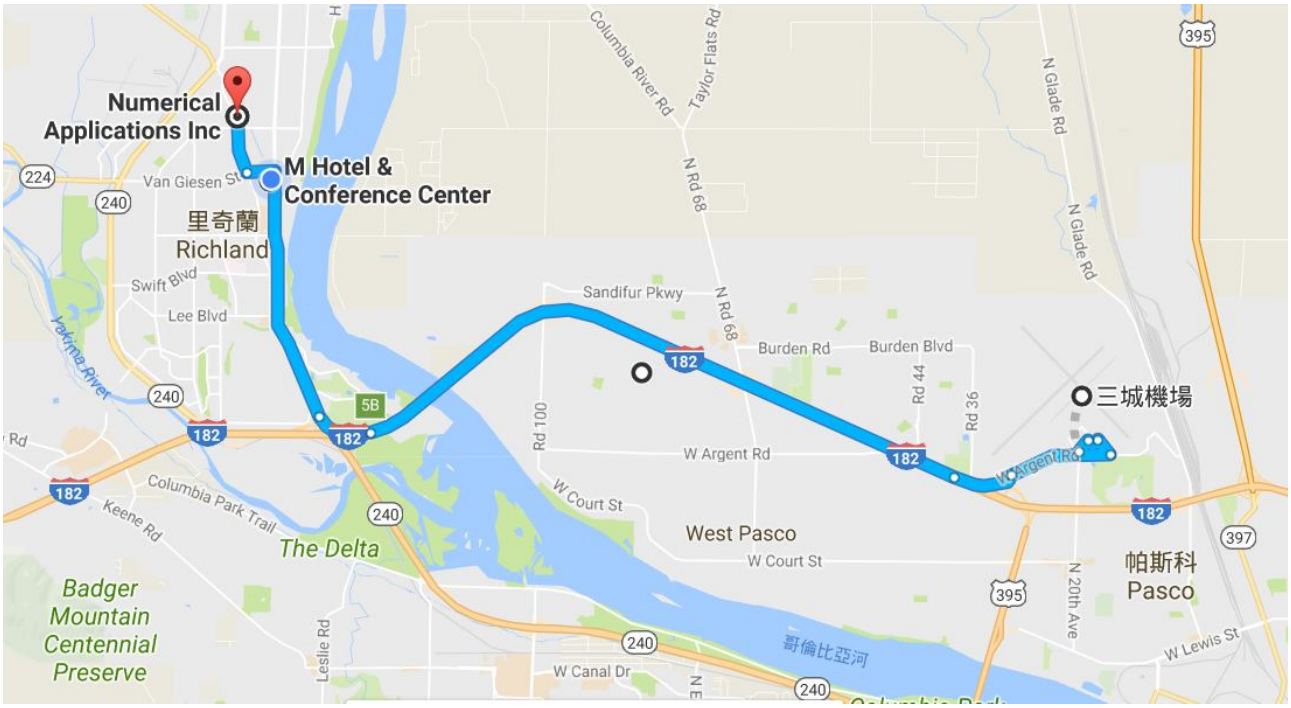


圖 1 本次公差前往之美國華盛頓州里其蘭市

圖 2 Zachry 公司在美國的其他辦公室

(二)核二廠輔機廠房設備驗證分析

首先由陳員向 NAI 人員介紹該項工作之緣由，核二廠終期安全分析報告(FSAR)並無明確指出放置於輔機廠房的 Motor Control Center (MCC) panel 的環境條件，然而廠家在評估其 thermal aging effect 採用了 FSAR Table 3.11-4 之嚴苛條件：事故前 6 小時 100°C、完全蒸汽狀態，6 小時至 100 天 65.6°C、相對溼度 90%。然而此條件對於 MCC panel 過於嚴苛，內部電子元件不可能在此狀態下仍發揮功能，若比照該條件，則無法找到符合要求的產品，造成核二廠在採購備品時的嚴重困擾，加上 MCC 相關設備並無其事故環境條件的分析基礎，因此委託本所進行分析工作。陳員的簡報如附錄(一)所示。

經與 NAI 的 Skip Denny 顧問和 Tom George 博士討論後，Skip Denny 顧問針對目前之分析模式提出之建議如下：

The following is a quick run through of the comments I provided on Monday morning, your Main Steam Tunnel (MST) model, then the RCIC break model.
Comments on INER models

MST

■ CVar 2c - In GOTHIC 8.1, CVars are returned in BRITISH units, not metric. Recommend conversion to metric and identifying units in the Description.

■ BC 15F & 16F - These are the break flows, but do not have ON Trips. ON Trips are convenient so that the model can be run as NULL to confirm nothing happens.

■ BC 15F & 16F - The break flows, P, and T, all appear to come from an outside source. It may be preferred to uncouple from a computed source by bounding the source M & E.

■ BC 15F & 16F - The pressure profiles (FFs 8T & 11T) may be simplified to atmospheric pressure to ensure all steam release.

■ Time Domain End Controls - You might want to change to OFF for all but the last Time Domain.

■ Data Tables 1T through 7T, heat sources for BCs 1F through 7F - Is a ramp down from 0s to 600s intended?

■ Heaters 1F through 7F all include mass flow rates of 4.72 m^3/s with heat rates of 1T through 7T. None have ON or OFF Trips. Is it intended that the heaters be heating liquid flow that then is boiled (a boiler)? Normally a heater that heats the air (Vapor) has no flow.

■ TCs 8 and 9 (10) are 60cm thick concrete (steel) slabs set initially at 40C. Volume 146 (MST) is initially at 54.44C, while the other side of these TCs are at 40C. It may be necessary to either set the initial temperature for the TCs to 54.44C or run a short duration null to develop a temperature profile through the TCs so that the surface in the MST is not 40C at the start.

■ MST initially pressurizes from the steam break, but blows down to atmosphere, leaving mostly steam and very little air in the MST. After the break isolates, almost only steam in the MST continues to condense on the walls, resulting in a large vacuum in the MST.

■ Material properties for concrete seem off. Your density is 100 kg/m^3 (6.2428 lbm/cuft) and specific heat is 21.39 kJ/kg*C (5.1089 BTU/lbm*F). But the product becomes about 30 BTU/cuft*F. We use a density of 144 lbm/cuft and specific heat of 0.2 BTU/lbm*F, with a product of 28.8 BTU/cuft*F, so the difference should not be significant.

■ BCs 1F through 14F are volumetric ins and outs for SGTS, with identical volumetric flow rates, pushing volume into a compartment, then removing at the same volumetric rate. If there is heat-up in the Compartment, this will result in (superficial) pressurization in the Compartment.

■ FPs that connect rooms and have the exact same bottom elevation as the rooms will tend to spread liquid collection across the rooms. It is advised to include a small curb between rooms by having the bottom of the FP perhaps 1/4 inch greater than the floor of the adjoining rooms. Any liquid collection in one room will puddle in that room before spilling over to adjoining rooms.

RCIC

■ Similar to the first model, but different. Verification of the second model is not simplified by the first model because constituent parts are numbered differently.

依據上述建議，Skip 顧問亦將我方提供之模式加以修改，包括重新繪製控制體積的大小位置，讓圖面更簡潔美觀。並建議熱導體可以使用程式內建之自動切割功能(Auto-divid)來切割格點，SGTS 啟動時的廠房進氣改用 Pressure boundary condition 處理，並建議調整廠房洩漏之面積或流阻，使其壓力平衡於-0.25 吋水柱高，會較合乎實際現象。而分析起始設置時間由 0 秒改為-5 秒，並將-5 秒至 0 秒時區的熱傳導 dt ratio 設為 1000 或 25000，讓熱導體內部出現合理的溫度梯度後，再開始事故的模擬。

Skip 顧問於 7 月 26 日將我方提供之主蒸汽管斷管事故與 RCIC 斷管事故兩模式合併，並提供以下說明：

Attached is the latest revision of the HELB model we have been working on together. This model now combines both the MSLB in the MST (Compartment 146) and the RCIC steam break in the RCIC room (Compartment 7). I offer a few notes on the model

■ The run currently starts at 0.0, same as your original. This means there is no temperature gradient built up in the Thermal Conductors (TCs) touching the Main Steam Tunnel (MST). These TCs all have their temperatures set initially to 40C, although the room is initially at 54.44C. But set the start time (Run Control/Run Options) to -5.0 seconds and GOTHIC will build up a temperature profile in these TCs prior to the break occurring when time reaches zero.

■ I've increased the graphing printout frequency early in the event so the graphs we get will better show what is happening. I've also added Time Domain changes when significant changes are happening (when the heaters stop decaying their heat and settle to the long-term heat rate, and again when SGTS initiates). This will ensure our plots show these changes.

■ I've also increased the allowed maximum time step later in the run, after SGTS initiates, to as much as 60 seconds. This allows the run to complete much faster.

■ I've redrawn all Flow Paths (FPs) so that the labels are back. I've also cleaned up the visual of the model.

■ The environment Compartment (147) is now a background, so any Flow Path or Thermal Conductor can attach more readily without need to draw back to some other area of the graphic. I've shrunk Boundary Conditions so they are less obstructive, visually.

■ We've changed the thermal properties for concrete (density, specific heat, and thermal conductivity), using values we typically use (SI Units, of course).

■ The first three TC Types are all 60 cm thick, including the TC you described as "NO. 90 door" that thermally communicates between the 4F corridor and the MST. Remember you were going to confirm that this is really intended to be a 60 cm thick slab of steel. We have left it as 60 cm thick. The RCIC model adds one additional TC Type, this one is a 137 cm thick concrete wall. We have removed the subregions in all of these TC Types and instead had GOTHIC auto-subdivide these TC Types so that the model will better predict the heat absorption into the TCs. Because the outermost region of the TC (surface) that sees the rapid temperature rise in the environment is now much thinner, the temperature of the TC surface facing the heating environment increases its surface temperature much quicker now, which then limits the heat being absorbed by the TC, resulting in an increase in the room temperature early in the event (conservative). So now all four TC Types have used the Auto-Divide feature in GOTHIC.

■ Surface Option 4 is the UCHIDA. Your model had the Conduction/Convection Option set to ADD, which will add the UCHIDA heat transfer and the Convection heat transfer. NUREG-0588 recommends (for evaluating environment temperature) using UCHIDA until the condensing heat transfer diminishes, then using natural convection, so I interpret this to mean using MAX instead of ADD. Your SO4 (as well as all other SOs) correctly sets the Forced Convection to OFF, so that is left as-is. But we've set SO4 to MAX instead of ADD.

■ I’ve also added an SO5 described as “Insulated” with the Heat Transfer Option set to “Sp Heat Flux” and the Nominal Value set to zero. It is a practice of mine to always include a SO like this. In this manner you could change the SO for either or both sides of all TCs to this Insulated SO to evaluate how much your heat sinks are affecting your run results.

■ All SGTS Boundary Conditions (BCs) are now three BCs. The first two are the same, but I’ve added a third. The first BC is the inflow where you are forcing a specified volumetric flow into the Compartment, the second is the outflow where you are forcing the same specified volumetric flow out of the Compartment. As we mentioned, this results in an increase in mass of air in the Compartment (for a heated Compartment) and thus an artificial pressurization. The added third BC is a Pressure BC with a valve on its FP. Trips 2 and 3 control which inflow is used. The model currently uses your same forced inflow (Trip 2 set to zero).

■ The MSLB in the MST (Compartment 146) now includes not two BCs but two sets of two BCs. The first set (BCs 24F and 25F) are as before and use your RELAP M & Es. But new BCs 26F and 27F use a constant Pressure of 1 atm, a constant enthalpy of 2803.17 kJ/kg (maximum enthalpy for saturated steam), and a simplified bounding mass flow rate that bounds your RELAP flows. This attempts to decouple your GOTHIC model run from your RELAP run as we spoke about. Trips 4 and 5 determine which MSLB source the model will use, while Trip 9 sets when the break happens.

■ The RCIC break is now included in the model as well and also has the two sets of two BCs. BCs 28F and 29F are again your RELAP M & Es, while BCs 30F and 31F are intended to be bounding. I have not yet developed the bounding mass flow rates for 30F and 31F, so these are not completed yet. Trips 6 & 7 determine which RCIC break M&E to use, while Trip 10 sets the time of this break.

■ So Trips 9 and 10 are used to set which break to simulate.

■ I have added a vent to the MST. The vent will open when pressure in the MST drops below 1 atm (pressure in the environment, Compartment 147), and will reclose when pressure increases again above 1 atm. I have not seen cycling, but if this is experienced, these setpoints can be changed slightly. Trip 1 sets when this vent becomes available, so set to infinity the vent will never open.

■ For your MST leak path, which draws from the MST and discharges to the 4F corridor, I noticed some of the flow being passed was liquid. If this is intended to be leakage, it may not be intended to pass liquid. Liquid was being passed because the FP used to draw flow (FP 105) had its bottom set to the bottom of the MST (13.3 m) and liquid collecting on the floor of the MST was being drawn into the leak. I’ve changed the bottom elevation and height for this FP 105 to be the same as the floor of the 4F corridor, which is also the same as the bottom and height of the FP passing the flow to the corridor. This has now kept from passing liquid as part of the leak.

■ I have left the flow rates (4.72 m3/s) in all of your heaters, but be aware that because these are heaters (and with positive heat rates) and the Phase Option is Vapor, these heaters will not use these rates. The intent of these rates for heaters is for use with heaters that have the Phase Option set to Liquid, to only heat a certain portion of the liquid, and the rest of the heat (if all liquid in the flow is evaporated) to pass to the vapor, but with the Phase Option set to Vapor as you have it, the heat is passed to the vapor as you intend.

除了分析模式改善之外，Skip 顧問也提供了些使用 GOTHIC 程式的小技巧，例如建立流徑(flow path)可刻意將其分為兩段，使流徑的標示會靠近其中一端的控制體積，讓模式圖較為整齊。並將代表大氣環境的控制體積放大成模式圖的背景，建立與大氣環境的流徑(例如 SGTS 的抽換氣流徑)就不會讓模式圖過於雜亂。

Skip 顧問亦建議，建立一個通用性較大的模式，無論是何種事故，因為模式中的體積、流徑及組件的編號是相同的，進行結果比對會方便許多。

另關於 SGTS 抽換氣效應，Skip 顧問與 Tom 博士提出下述建議：

The impact of the assumed SGTS flow rate for the Aux. Bldg. HELB analysis was discussed. Since the SGTS flow is the only long term cooling mechanism modeled, the long term temperature is directly related to the assumed SGTS flow. The following is recommended:

■ Review plant operating procedures to identify other possible long term cooling mechanisms that could be included in the GOTHIC model.

■ A conservatively low estimate of the SGTS flow should be used. This could be determined from building leakage testing data. However, it should be recognized that this low flow value would be subject to any building modifications that would restrict building in leakage.

目前我方使用一個流量邊界條件模擬 SGTS 的抽氣效應，並使用另一個流量邊界條件處理外界洩漏至廠房的流量，此方式雖然直觀，但過於簡化，不易呈現 SGTS 能維持廠房在事故後負壓(-0.25 吋水柱高)的能力。Skip 顧問建議採用 volumetric fan 組件來模擬 SGTS 抽氣效應，並改用壓力邊界處理外界大氣洩漏進入廠房的流量。雖然此方式較為合理，一方面需要 SGTS 完整的設計資料(例如風扇特性曲線)，且需經測試才能合理設定洩漏流徑的面積及流阻，我方計畫執行時程較無法配合，且我方計畫之目的是找出較保守的廠房溫升，探討事故後廠房負壓狀況並非計畫目標，故我方仍暫時維持目前 SGTS 抽換氣處理方式。

此外，我方在主蒸汽管斷管(圍阻體外)、爐水淨化系統(Reactor Water Cleanup system, RWCU)斷管、爐心隔離冷卻系統(Reactor Core Isolation Cooling, RCIC)斷管等事故中，係採用 RELAP 程式計算的斷管沖放數據，包括流量、流體焓、壓力等數據。圍阻體或廠房熱流分析常會需要其他程式提供沖放數據，Skip 顧問依據其個人經驗，建議不要直接使用沖放數據，而是先建立較保守之包封曲線(envelope curve)，其能涵蓋其它程式提供之沖放數據，以圖 3 為例，包封曲線能涵蓋 RELAP 提供之沖放流量，可以得到較保守之結果。流體焓亦可採用相同方式，會有較多能量進入圍阻體或廠房空間。

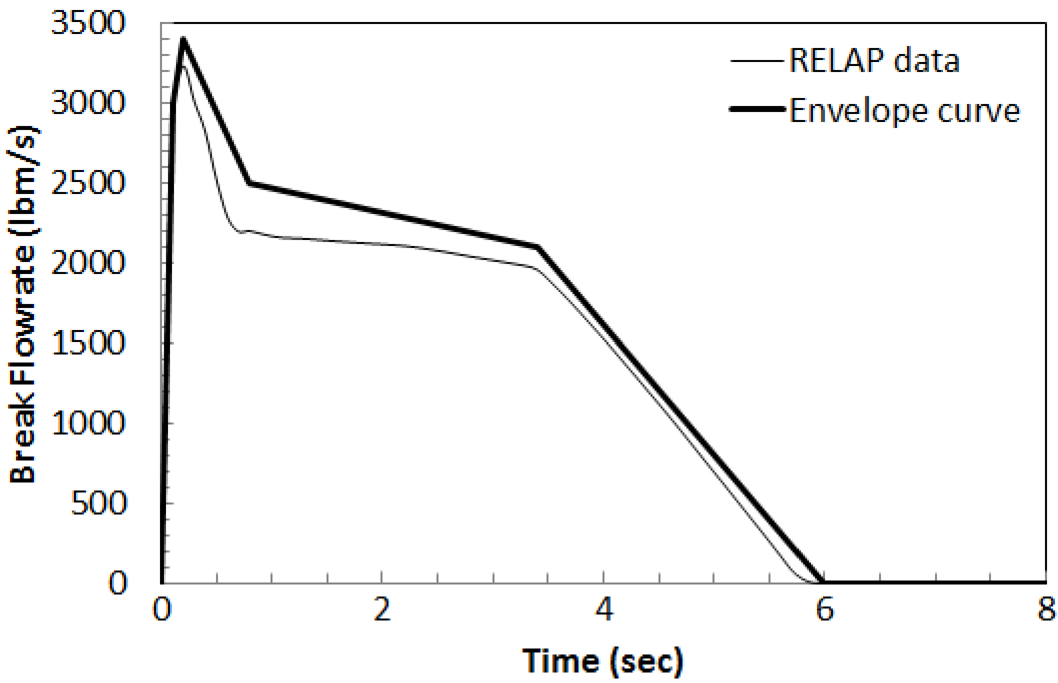


圖 3 沖放數據包封曲線示意圖

經過數天討論溝通後，NAI 將我方提供之廠房模式重新修改，如圖 4 所示。修改過的圖面較清爽，也較易於和工作同仁討論模式內容。

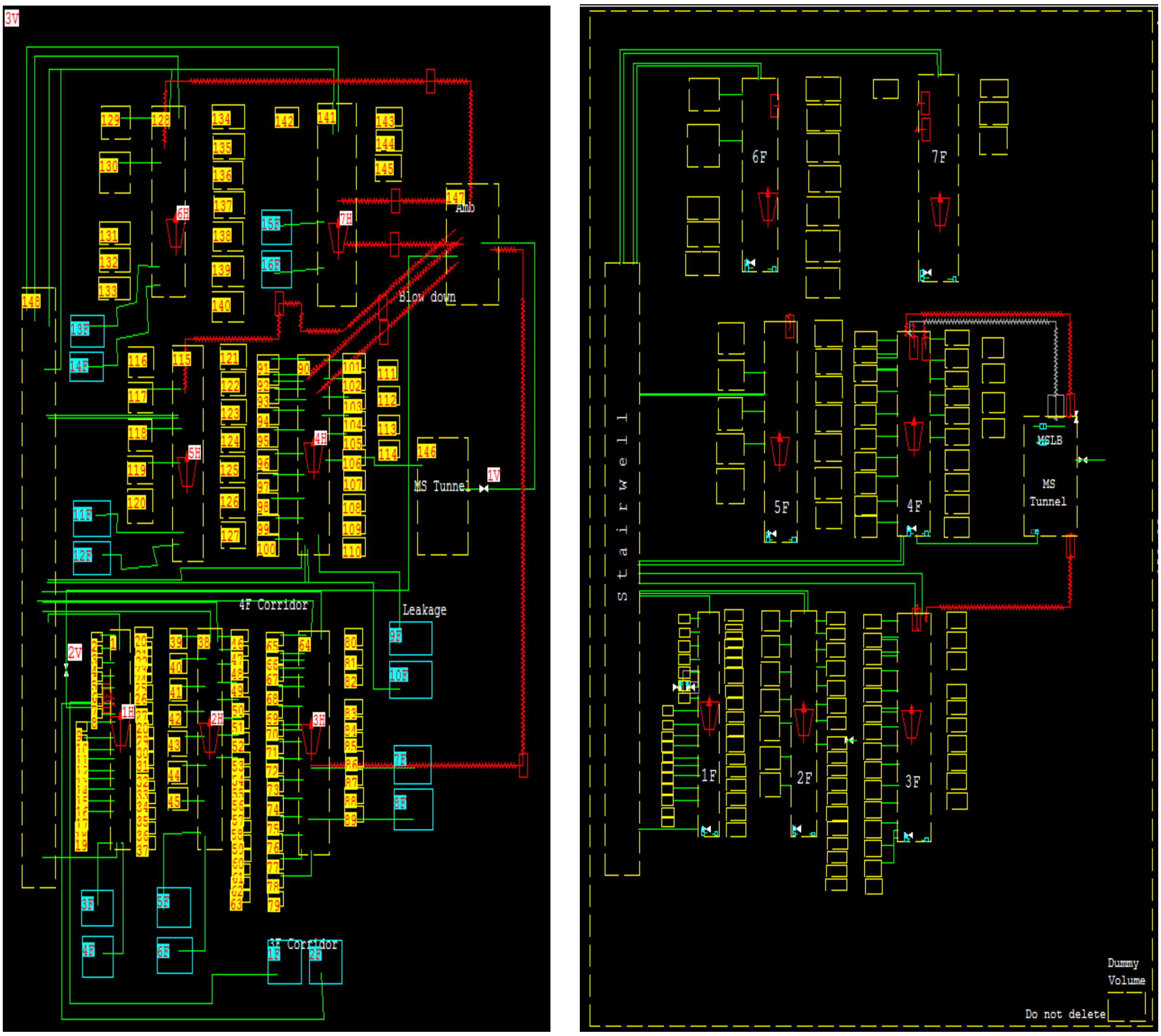


圖 4 經 NAI 修改前(左)及修改後(右)之模式圖

(三)用過燃料池 GOTHIC 分析模式

此項工作由位於 Stonington 辦公室的 Jared Zankowski 先生經由視訊連線，說明使用三維模式建立之用過燃料池模式。該模式係參照壓水式反應器(PWR)電廠的用過燃料池，將其分割為數個三維體積，如圖 5 所示。該模式經由外加的 Dynamically Linked Library (DLL)設定衰變熱功率分佈，以及產生鋯水反應後的氫氣與熱源產生量。

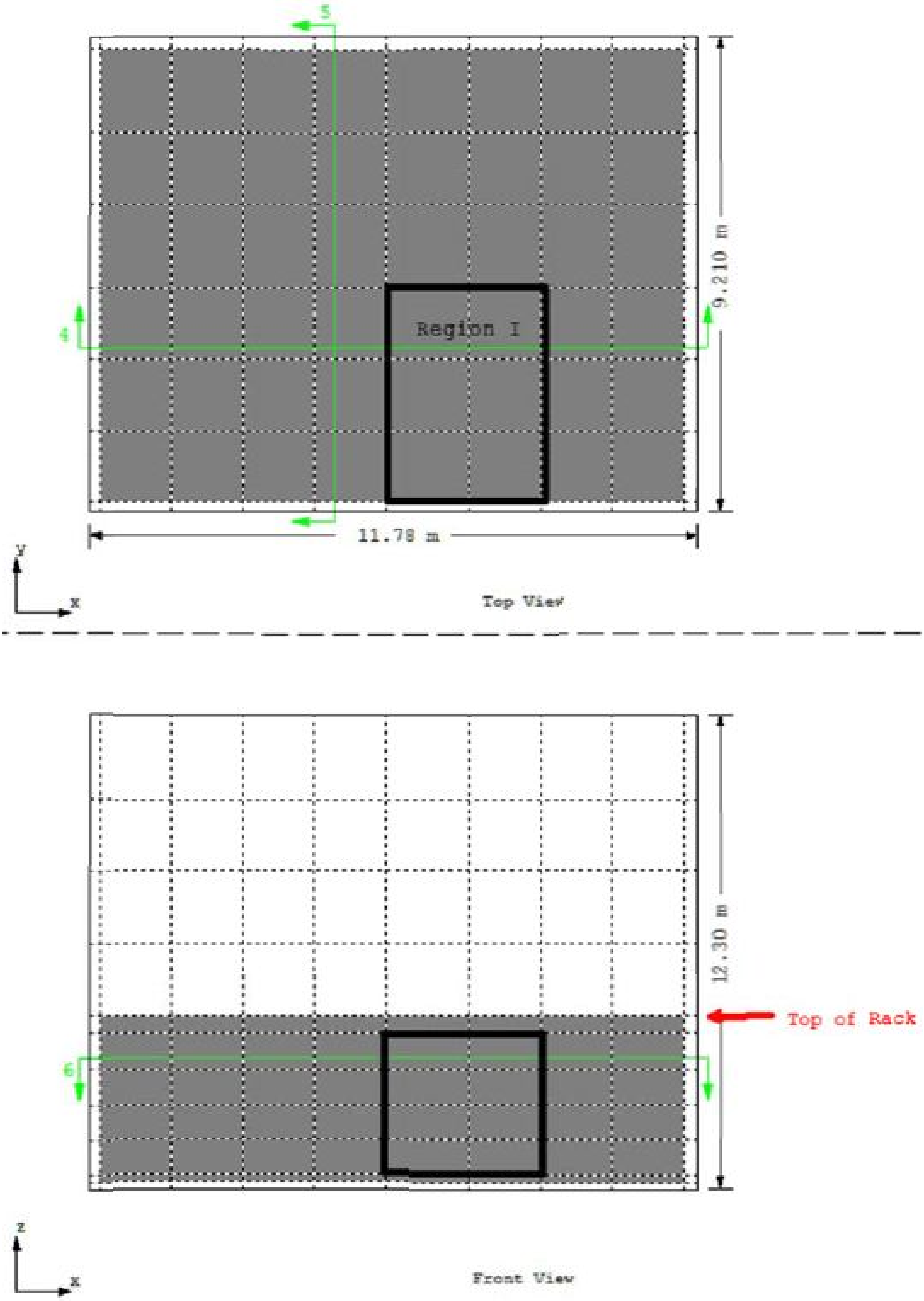


圖 5 用過燃料池之三維 GOTHIC 模式圖

該模式可用於並計算其在失水事故狀況下，燃料的溫升變化。假設用過燃料池發生大裂縫導致池水完全喪失，Region I 燃料之單位體積熱源為 750 kW/m³，計算出的燃料溫升如圖 6 所示，由於沒有液態水有效冷卻，燃料護套溫度急劇上升，並因鋯水反應而產生氫氣，如圖 7 所示。較可惜的是，因為該模式有使用 DLL 進行外部聯結，該模式需在有安裝 Microsoft Visual 的電腦上執行，且因 DLL 之故，該模式僅能使用單 CPU 計算。

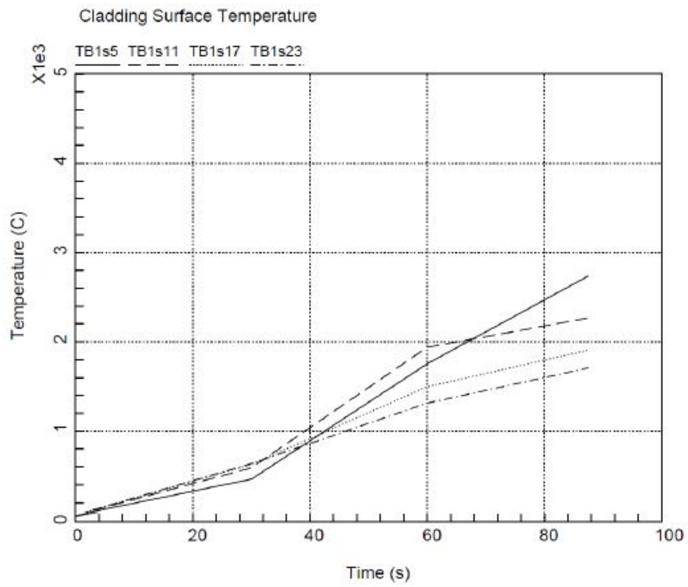


圖 6 用過燃料池完全失水事故的燃料護套溫升

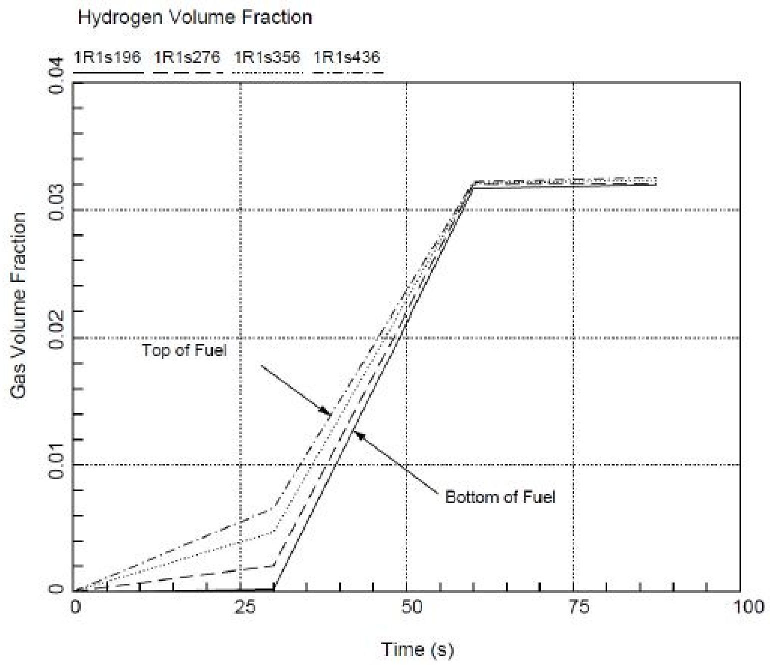


圖 7 用過燃料池完全失水事故的氫氣體積分率

該分析模式僅是作為研究探討，沒有考慮任何的搶救措施，也不代表用過燃料池會發生大裂縫。依據美國 NRC 發布 NUREG-2161 (Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor)，即使發生超過設計基準之地震，依據結構分析結果，用過燃料池所產生之最大裂縫等同於一個直徑 4.5 英寸的開口。且國內電廠已依照該份指引額外建立了 500 gpm 補水與 200 gpm 灑水措施，最新退出燃料亦會與舊有燃料採用 1x4 排列(即一束最新燃料四周皆是舊有燃料)，可有效防止事故發生的嚴重程度。

(四)臨時提問議題

1.圍阻體 pool swell 現象

我方提問 GOTHIC 程式對於圍阻體 pool swell 現象之處理能力，Tom 博士表示 NAI 以前曾使用 GOTHIC 的一維模式與 GE 公司的結果比對過，Skip 顧問亦提供以下書面說明：

Regarding Pool Swell for Mark III containments, the NRC document NUREG 0978 has good information. Figure 3-2 of this NUREG provides a curve of maximum pool swell velocity versus Drywell pressure (should be understood to be differential pressure, Pd – Pw). Using this figure, given a containment pressure response for an event, you could read what the maximum pool swell velocity should be. I believe the document directs Mark III owners to use a maximum pool swell velocity of 50 feet per second.

So the way GE would evaluate an event would be to generate the containment pressure response, including the Pd – Pw, then read the maximum pool swell velocity from Figure 3-2 of NUREG 0978 and confirm that the corresponding velocity is less than the design value used by the plant, which we expect to be 50 feet per second.

How to do this with GOTHIC is, once we have a good benchmark GOTHIC model that adequately duplicates the GE result, we can then run our difference case and compare the differential pressure (Pd – Pw) against our benchmark and confirm the our dP in our case is less than the benchmark case. Of course the GOTHIC model has to provide an adequate benchmark that captures the important phenomena of the event.

2.乾式貯存(Dry cast storage)

NAI 安排位在 Cary 辦公室的 Jeffrey Lane 先生說明目前 GOTHIC 程式應用在乾式貯存的狀況，由於牽涉廠家智慧財產，許多資料不能透露，但仍簡要地說明分析模式的基礎概念，其簡報如附錄(二)。相較於已有多起成功案例的圍阻體與廠房事故分析，GOTHIC 對於乾式貯存的應用是較為少見的。

藉由 GOTHIC 程式建立之乾式貯存桶模式如圖 8 所示，藉由設定對稱的邊界條件，計算區域僅包含 1/4 的乾貯桶。分析假設中央的燃料束(圖中的 FA #1)有較高的熱負載，該區域使用三維模式處理，可以得到較精確的自然對流效果；而其餘燃料束則使用一維模式處理，則可節省計算資源與時間。

目前 NAI 對於乾式貯存桶熱流分析並無太多經驗，模式也在發展修改中，且因牽涉廠家智慧財產，並無呈現分析結果。但乾式貯存的熱流分析是未來 GOTHIC 程式的應用方向之一。

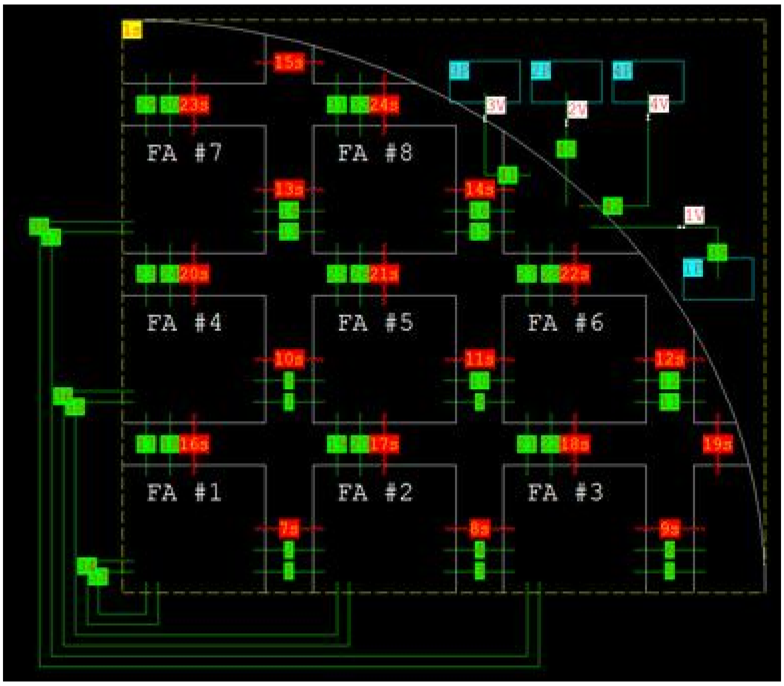


圖 8 乾式貯存桶 GOTHIC 分析模式

3. Inter Process Communication (IPC)

因應我方要求，Tom 博士展示了 GOTHIC 的 IPC 功能，該功能允許 GOTHIC 與其它程式進行耦合計算。例如本所核工組在分析反應爐喪失冷卻水事故時(Loss of Coolant Accident, LOCA)，先使用 RELAP 程式計算反應爐的熱流變化，以其計算出的斷管沖放流量與流體焓等資料作為 GOTHIC 圍阻體模式的邊界條件，再進行 GOTHIC 圍阻體熱流分析。而 IPC 功能允許兩程式能同時耦合進行運算，上游的反應爐模式可以即時得到圍阻體壓力變化的回饋，下游的圍阻體模式亦可直接得到沖放條件之變化。

Tom 博士表示，該公司最常使用的 IPC 是不同 GOTHIC 案例之間的耦合運算，並以過去處理電廠管路內氣泡沉積現象舉例說明，NAI 曾協助評估美國某電廠內發現緊急爐心冷卻系統(Emergency Core Cooling System, ECCS)管路內有氣泡出現，該系統水泵運作時，可能會導致水槌現象出現，對管路結構有不利影響。由於要掌握氣泡位置，因此管路須分為許多體積處理，然而該電廠發現氣泡會出現不同系統的管路中，須將許多系統皆納入分析範圍內。若僅以單一模式包含所有系統，該模式會過於龐大，因此 NAI 將其分為 7 個模式，各模式間以邊界條件交換資料(壓力、溫度、流量)，IPC 不僅避免了在單一模式包含過多系統管路的問題，且各模式可由不同工程師負責，藉由 IPC 可有效管理整合每個模式。

Tom 博士亦當場提供一範例進行現場練習，模擬長度為 50 ft 的直管，上游壓力為 300 psia，管路初始壓力為 200 psia，其尾端突然被閥關閉時的壓力震盪。首先建立一個模式代表整條管路，其包含 50 個一維體積；再分別建立兩個模式代表管路上下半段，各自包含 25 個一維體積，藉由 IPC 將管路上下游模式進行耦合，將上游最後一個體積的流量傳給下游模式，並把下游第一個體積的壓力回傳給上游模式，模式示意圖如圖 9。

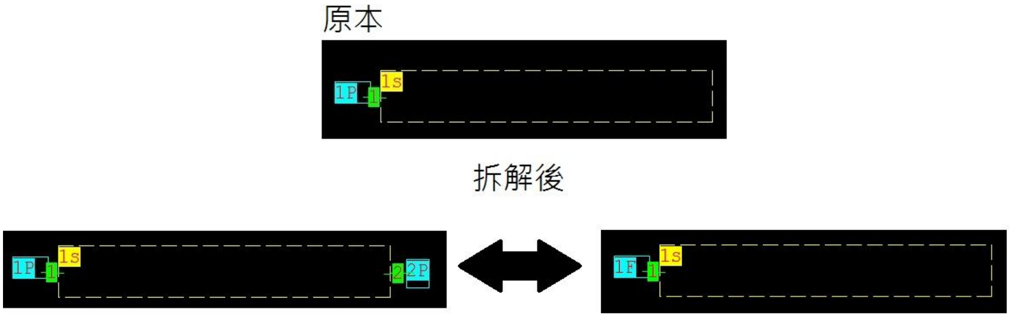


圖 9 IPC 範例模式示意圖

圖 9 上方的單一管路模式計算所得之第 5、25 及 50 個體積的壓力變化如圖 10 所示，而。圖 9 左下方的上游管路模式計算所得之第 5 及 25 個體積的壓力變化，以及圖 9 右下方的下游管路模式計算所得之第 25 個體積的壓力變化如圖 11 所示，其結果與單一管路並無明顯差異。

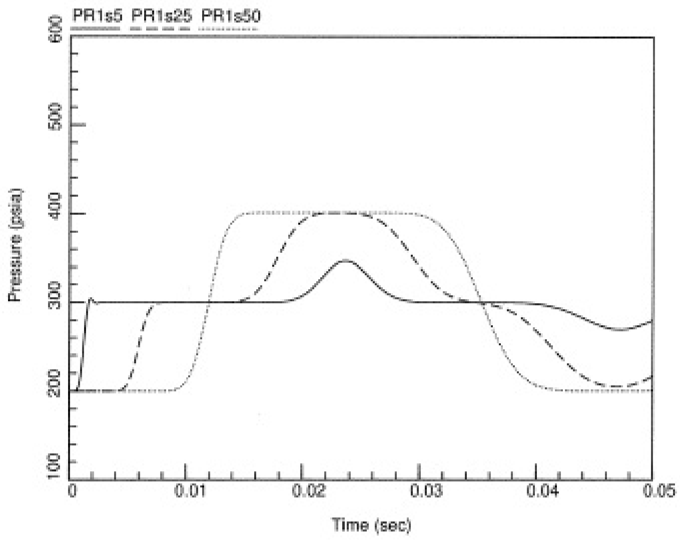


圖 10 單一管路模式計算所得之壓力變化

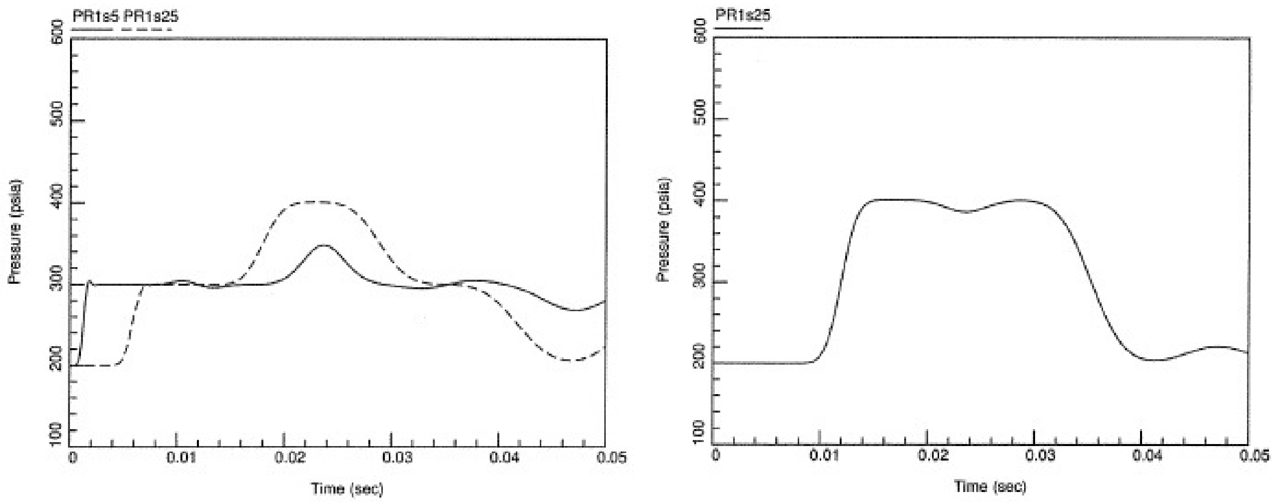


圖 11 上下游管路模式經 IPC 耦合後所得之壓力變化

4.替代衰變熱移除以及替代停機冷卻

因應我方提問，Skip 顧問說明關於替代衰變熱移除(Alternative Decay Heat Removal)及替代停機冷卻(Alternative Shut Down Cooling)之概念。替代衰變熱移除係指在大修過程，反應爐開蓋後，反應爐穴(Reactor Cavity)與用過燃料池連通，如果餘熱移除(Residual Heat Removal)系統因檢修而不可用，需依靠用過燃料池冷卻系統來移除池中與爐內燃料的衰變熱，如圖 12 所示。Skip 顧問曾使用 GOTHIC 建立反應爐與用過燃料池的模式，分析爐穴區域的流場，確認吸收爐內燃料衰變熱的池水能流至用過燃料池進行移熱。

替代停機冷卻(Alternative Shut Down Cooling)則是在反應爐遇到無法正常狀況停機冷卻時，先關閉主蒸汽管隔離閥(Main Steam Isolation Valve)、汽機控制閥(Turbine Control Valve)或斷止閥(Turbine Stop Valve)，再將反應爐內水位提高至主蒸汽管之上，爐水進入主蒸汽管後，再經由安全釋壓閥管路到達抑壓池(suppression pool)，最後由 RHR 系統抽取抑壓池水進行冷卻，再注水回反應爐內，如圖 13 所示。

Skip 顧問表示相關模式都還在發展，並沒有展示成果，但也表示相關議題可能會有電力公司需要，會繼續發展與改進分析模式。

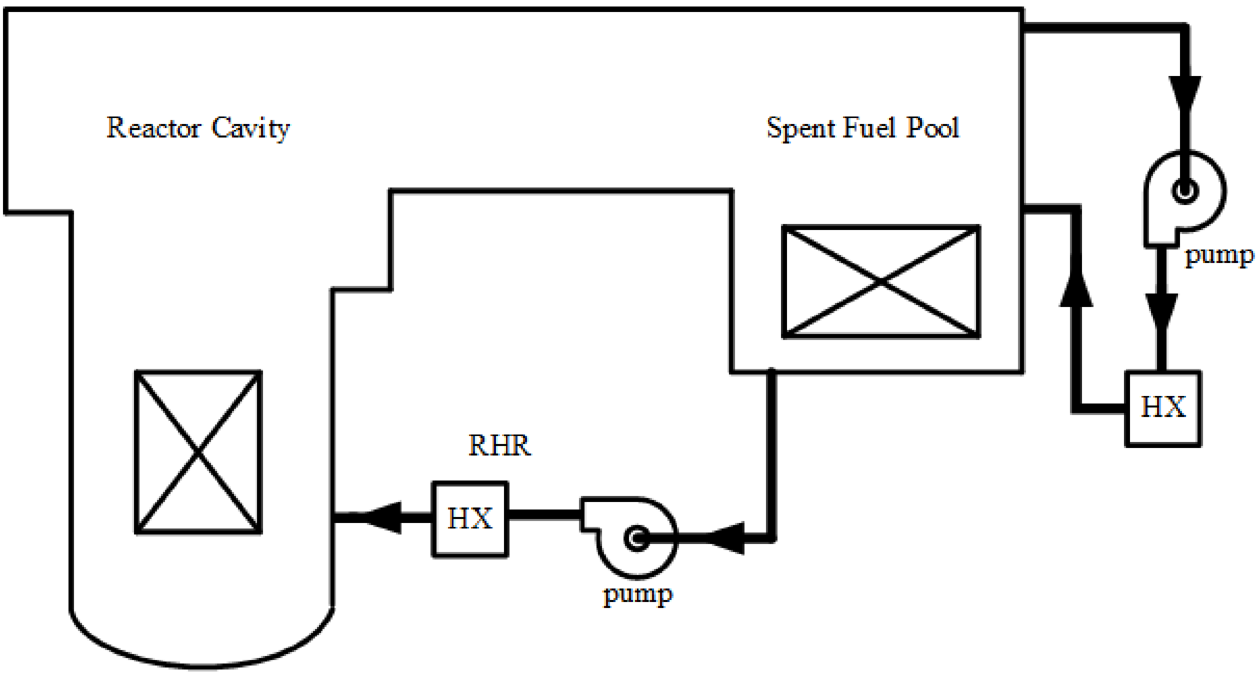


圖 12 替代衰變熱移除之示意圖

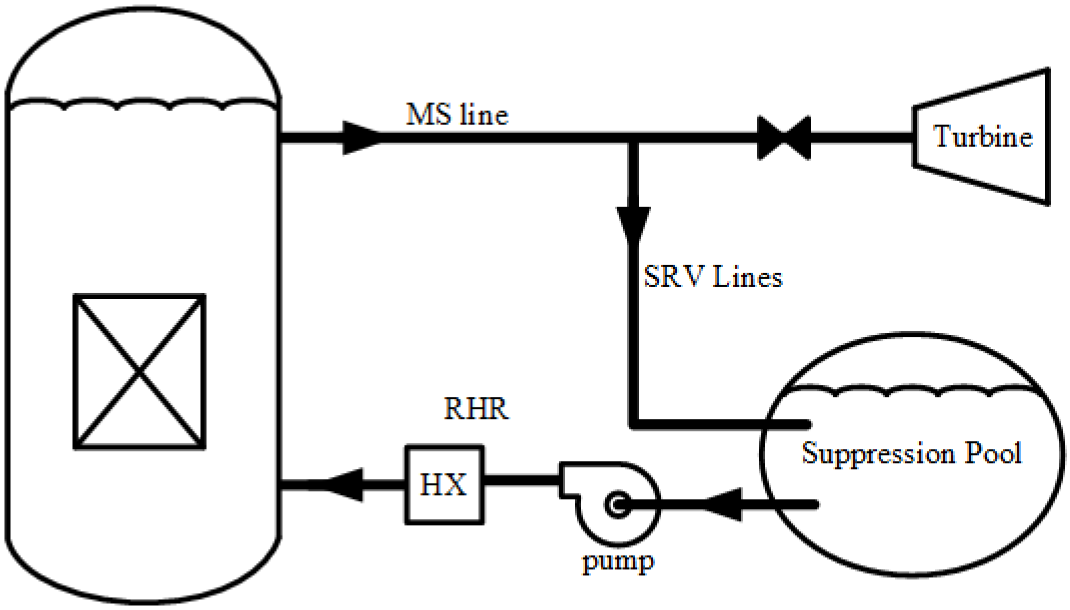


圖 13 替代停機冷卻之示意圖

三、心　得

(一) 本次公差有機會與 NAI 人員交流，除了原始發展者 Tom George 博士，Skip Denny 顧問也提供了許多使用上的技巧，包括整理模式節點圖、採用保守的沖放數據等技巧。Skip 顧問表示他個人過去常向管理階層報告，將模式節點圖整理地較為乾淨，不但有助於審視模式，亦有益於向管理階層溝通。而採用保守的包封曲線涵蓋沖放數據，可以避免反應爐分析模式有輕微修改時，下游的 GOTHIC 圍阻體或廠房模式也要跟著修改的麻煩。

(二) 除了 Richland 辦公室，Zachry 公司亦有 Cary 及 Stonington 兩辦公室的人員支援。此二辦公室位於美東，與 Richland 辦公室約有 3 小時的時差。然而各辦公室人員常藉由視訊交換意見，即使各辦公室分處美東或美西，亦能有效降低溝通上的時間成本，益於工作效率之提昇。

(三) 目前 Zachry 的 Richland 辦公室僅剩 8 人，前幾年曾來訪本所核工組的 Donald Todd 博士與 Nate Carstens 博士也已離開 Zachry 公司，甚為可惜。但 Zachry NAI 仍因過去長年累積的 GOTHIC 發展經驗，加上美國核能市場有足夠需求，該程式的能力與應用範圍逐漸提昇，目前的 8.2 版已有計算 Neutron Kinetics 的能力，8.3 版可能會於明年正式釋出。

四、建　議　事　項

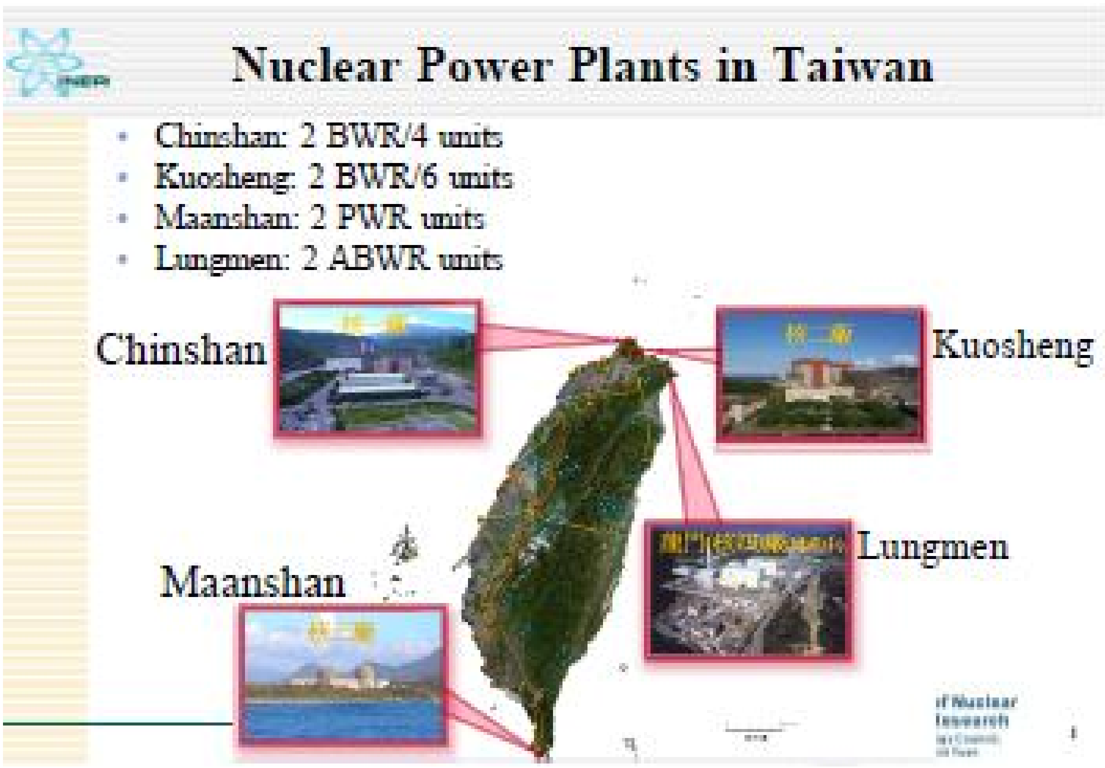
(一) 本所目前已與台電公司合作完成五本 GOTHIC 程式相關的專題報告，並通過原能會的專業審查，建立所內 GOTHIC 程式的使用能力，但持續與國外使用者及廠家的交流仍是必要的；除了增進核能安全分析能力外，更重要的是得知國外發展與相關應用的狀況。建議適時參與國際會議或與國外廠家交流，將有助於本所在技術能力的發展並擴展同仁技術能力。

(二) Zachry 公司在 Richland 辦公室雖然人員不多，但因其能夠維持住重要核心人員，以致能繼續培養新進人員，保有活躍的研發能量，維持其在市場上的競爭力。有鑑於此，本所現亦有人員屆齡退休而新進人員較多的世代交替期間，建議所內持續推動師徒制及建立關鍵技術等辦法，以提昇新進人員的技術能力，有效的作技術經驗傳承，維持本所在核能安全分析的專業研發能力。

(三) 經與 Zachry 公司 Skip 顧問數天探討相關議題，Skip 顧問很強調模式圖的簡潔，會有利於向其他人員、甚至是非技術人員之間的溝通。對於技術人員而言，與他人溝通要更進一步設身處地思考，考量對方的知識背景及對議題的瞭解程度，以達到有效的溝通。新進人員較易把重心放在研究工作，而忽視與他人討論或簡報的重要性，建議適時增加人員表達或說明的機會，將有助於增進本所同仁的能力。

五、附　錄

(一)我方向 NAI 介紹目前核二輔機廠房事故環境分析之簡報



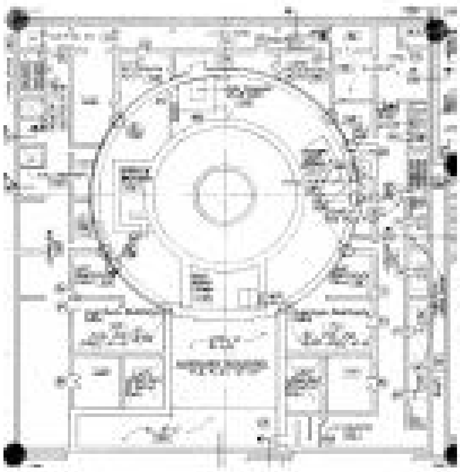
Kuosheng Plant

- The second nuclear power plant in Taiwan
- Located in New Taipei City
- Two units of GE-designed BWR/6 with the Mark III containment

Institute of Nuclear Energy Research

Auxiliary Building of the Kuosheng Plant

- The building surrounding the Reactor Building (primary containment)
- There are 7 floors



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EQ conditions

- Kuosheng FSAR Table 3.11-4
  - 0 to 6 hours
    - 212°F, 2 psig, all steam
  - 6 hours to 100 days
    - 150°F, 0.5 psig, 90% relative humidity
- These conditions are too tough for the Motor Control Center (MCC) panels.
- Unfortunately, there are no EQ documents about the MCC panels.

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Kuosheng Auxiliary Building model

- GOTHIC 8.1 is used.
- Four High Energy Line Break (HELB) events are considered.
  - Main Steam Line Break (MSLB) inside containment
  - MSLB outside containment
  - Reactor Water Cleanup (RWCU) system line break
  - Reactor Core Isolation Cooling (RCIC) system line break

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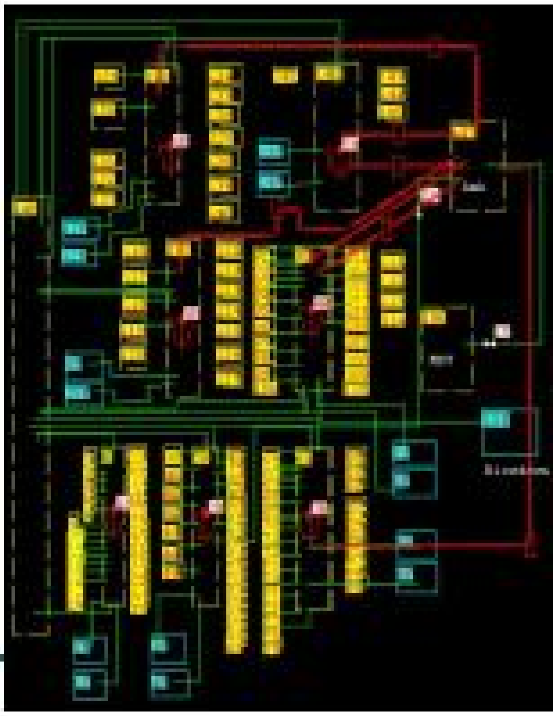
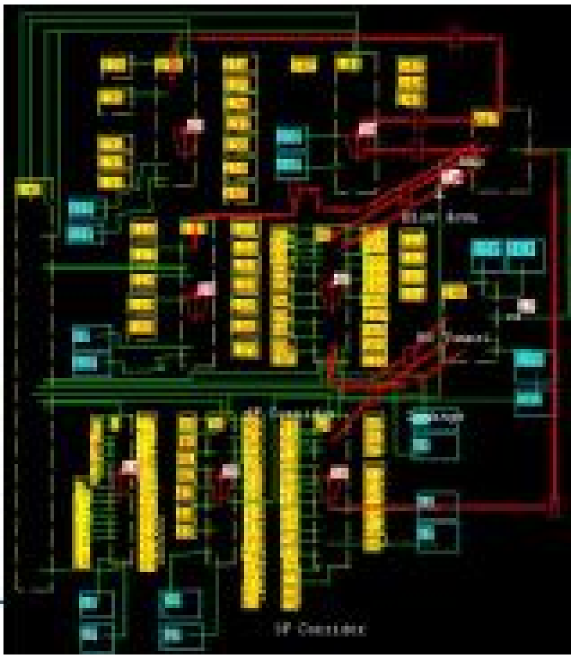
Kuosheng Auxiliary Building model

- MSLB inside containment
- Steam leakage from the containment



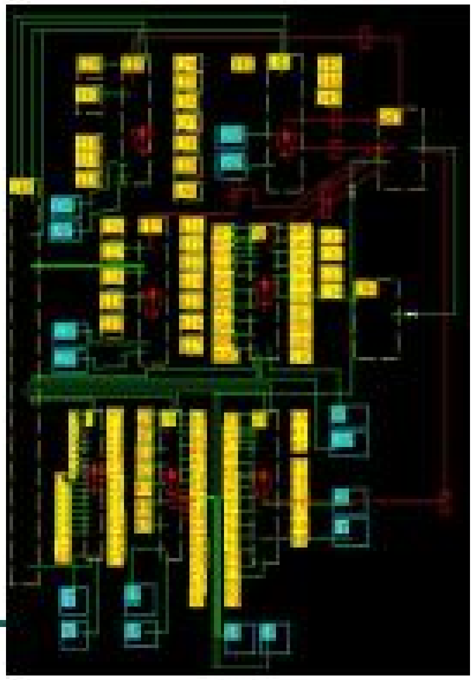
Kuosheng Auxiliary Building model

- MSLB outside containment
- A door connected between the mainsteam tunnel (MST) and 4F of the auxiliary building.
- Pressure relief doors in the MST are used to prevent overpressurization.
- Blowdown data is from RELAP5 calculation.



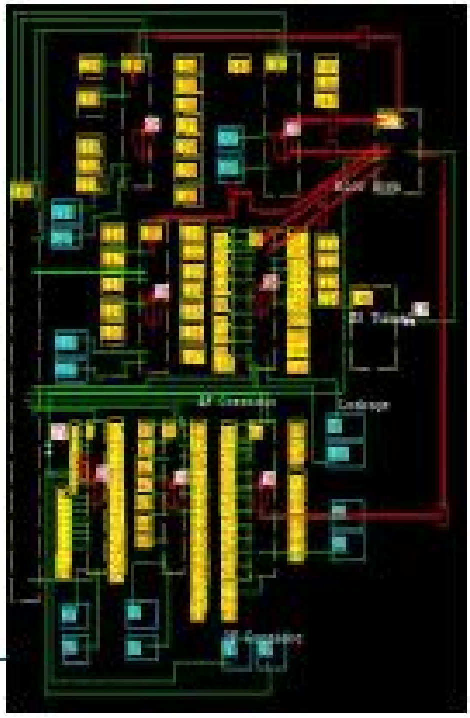
Kuosheng Auxiliary Building model

- RWCU line break
- Break occurs in the RWCU pump room which is in the 2F.
- A water-proof door which can stands 15.3 psig is for the room.
- Rupture disks in the pump room are used to prevent overpressurization.
- Blowdown data is from RELAP5 calculation.



Kuosheng Auxiliary Building model

- RCIC line break
- Break occurs in the RCIC pump room which is in the 1F.
- A water-proof door which can stands 15.3 psig is for the room.
- Rupture disks in the pump room are used to prevent overpressurization.
- Blowdown data is from RELAP5 calculation.



Kuosheng Auxiliary Building model

- The HVAC is assumed inoperable during the accident.
  - Venting flow: 50,000 gpm in total
- The Standby Gas Treatment (SGTS) system is responsible for the venting during the accident.
  - Exhausting flow: 7,000 gpm in total
- Heat sources from solar and lighting are considered.

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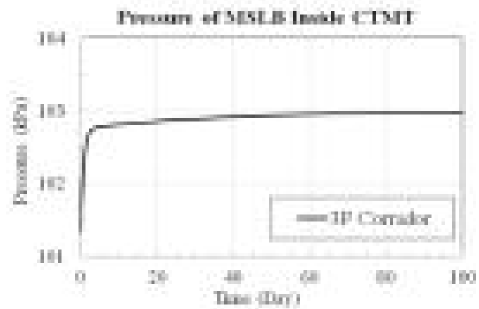
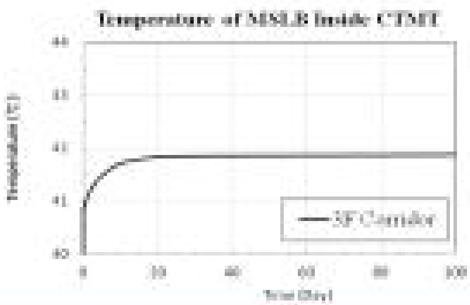
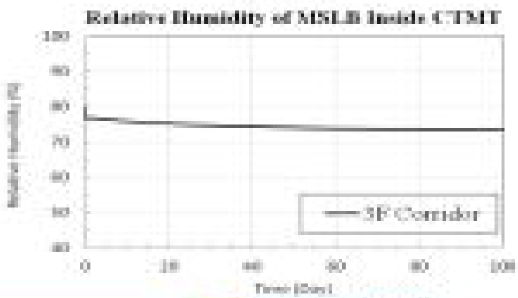
MSLB inside containment







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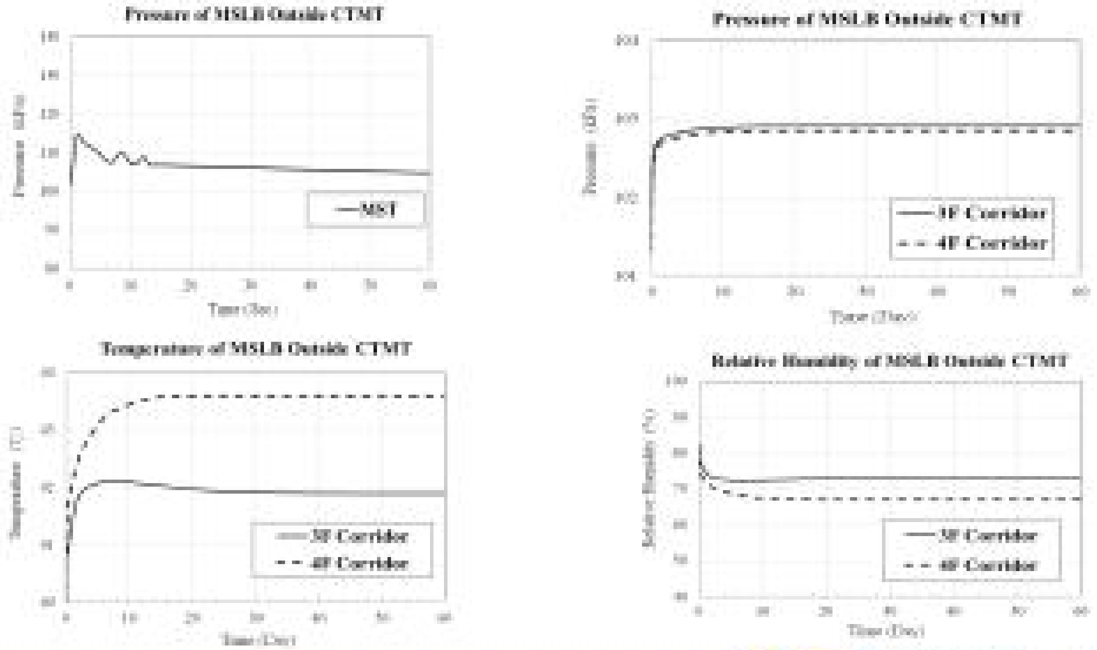
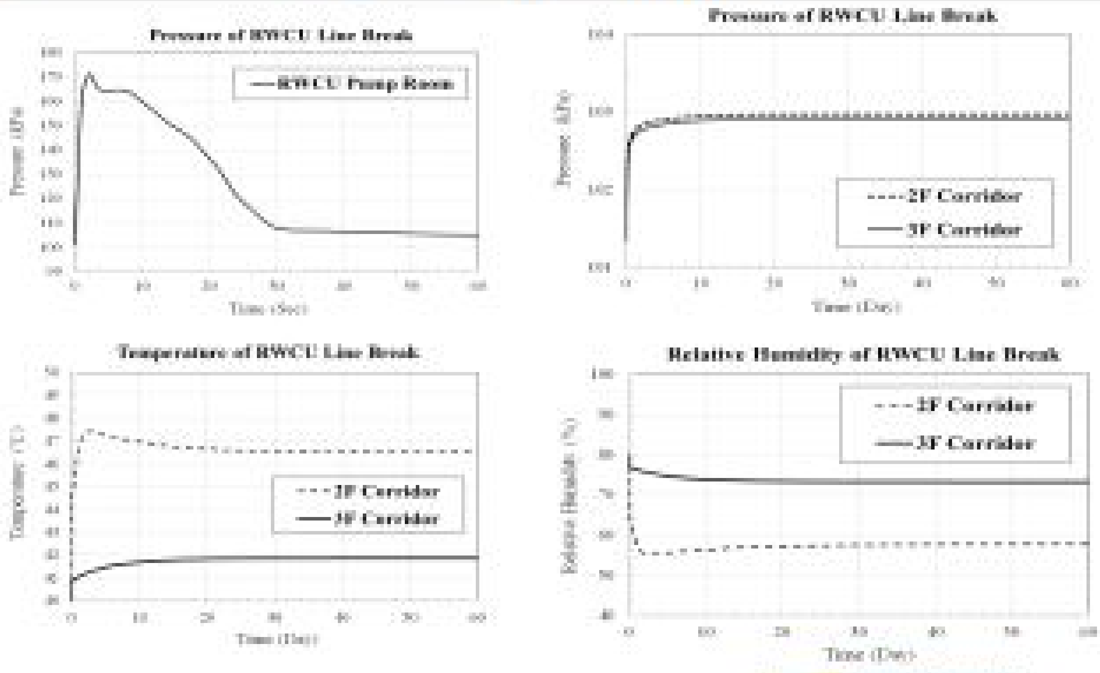
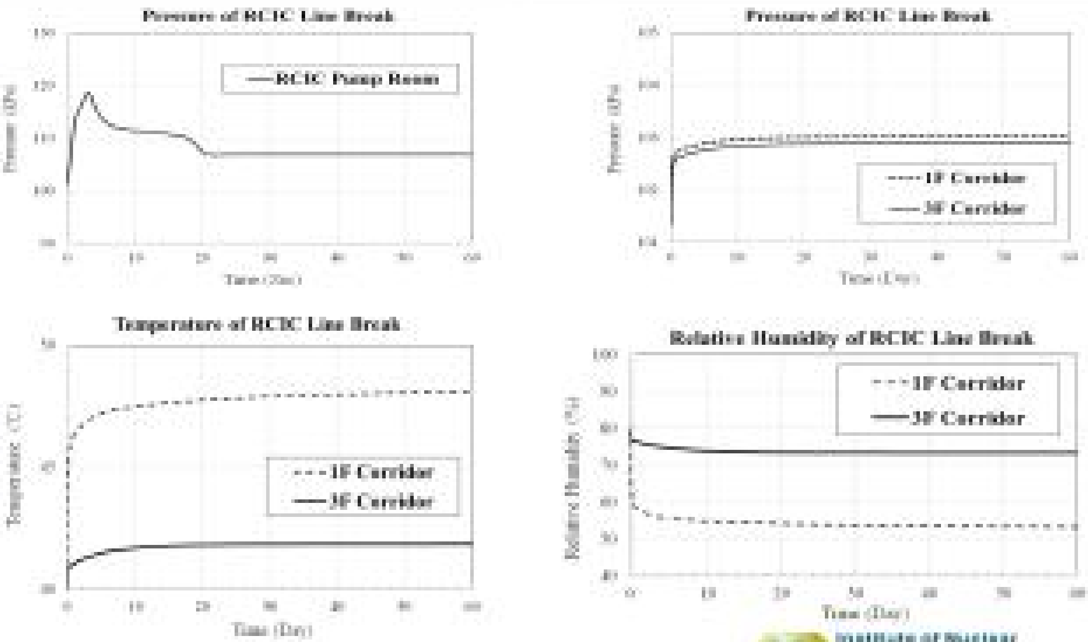
MSLB outside containment



RWCU line break



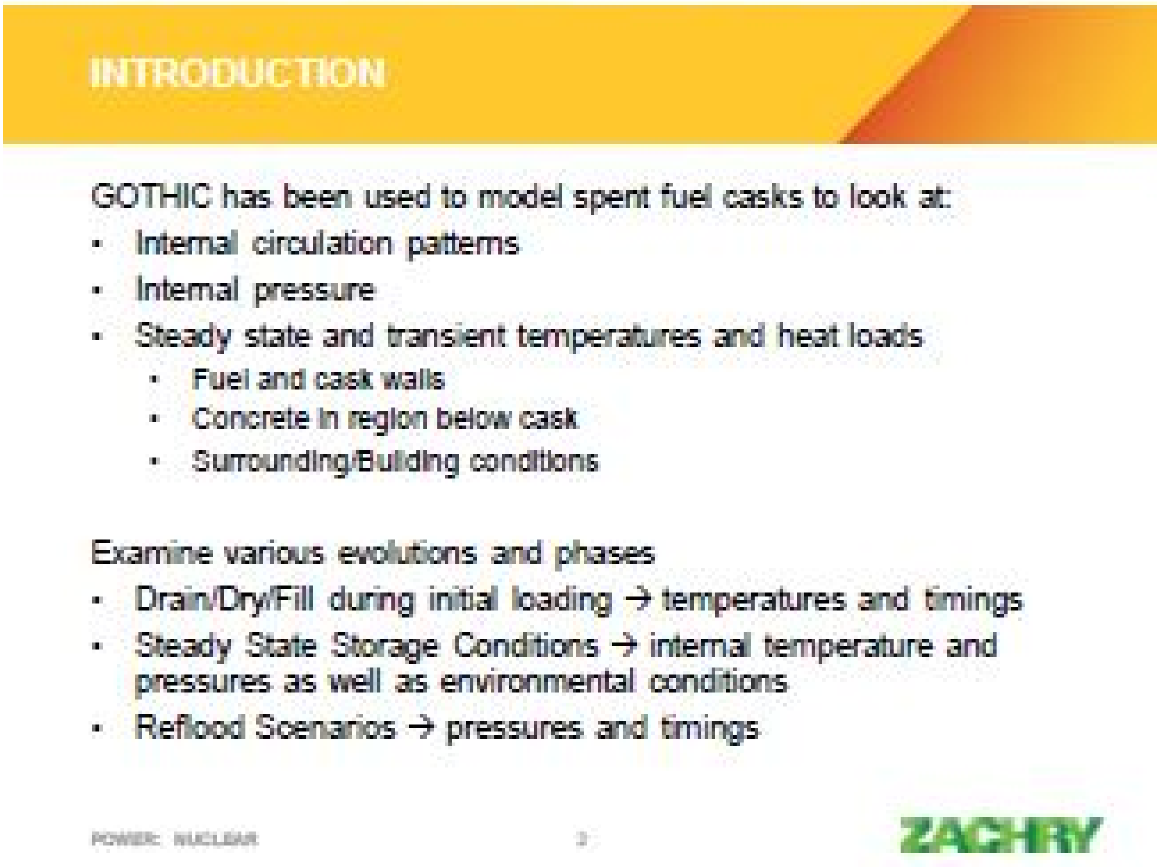
RCIC line break



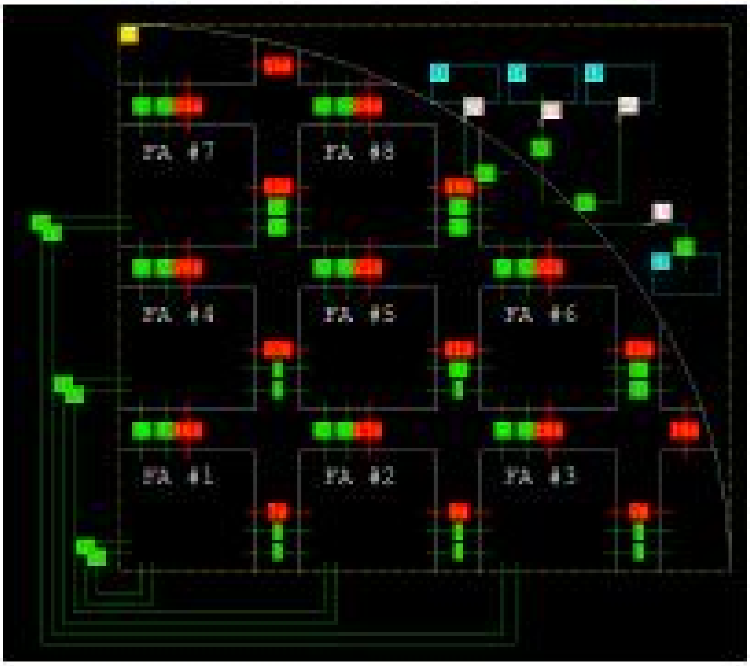
Conclusions

- For the corridor in the 3rd floor, the peak pressure after the accident is 0.24 psig, the peak temperature is 107.8°F, and the relative humidity is below 80%.
- There is sufficient margin to modify the EQ profile for the MCC panels.

(二) NAI 向我方介紹 GOTHIC 應用於乾貯系統熱流分析之簡報



EXAMPLE



RELEVANT CAPABILITIES

Flexible nodalization scheme

- Detailed model has center fuel assembly in 3D with individual fuel pins to consider local flow patterns and pin temperatures
- Other fuel assemblies modeled as 1D with the fuel pins lumped as a single thermal conductor for each assembly
- Allows for the model to remain computationally efficient while still considering both local and macroscopic effects

Buoyancy driven natural circulation flow

Transient conduction

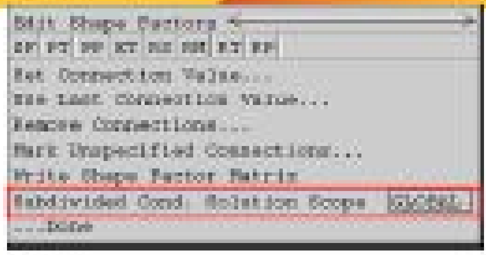
- Axial and radial power profiles
- Some capability for 2D conduction

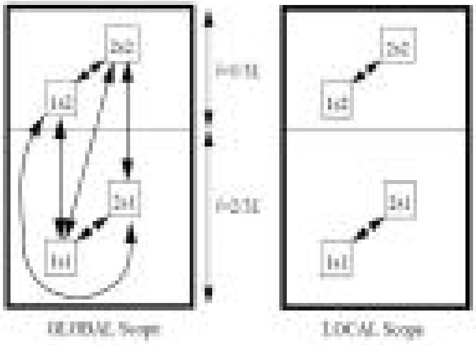
Radiation Heat Transfer

- Wall ⇔ Wall - transparent media
- Wall ⇔ Steam

LIMITED SCOPE RADIATION MODEL – GOTHIC 8.1

- In Version 8.1 a new option was added to limit the scope of the radiation solution
  - GLOBAL - all radiation surfaces can see each other
  - LOCAL - scope limits radiation connections limited to conductors and subconductors in the same horizontal plane
  - Limited scope is particularly useful for modeling radiation in rod bundles





LIMITED SCOPE RADIATION MODEL – GOTHIC 8.2

Thermal Conductors - Table 2

Cond #	Therm. Rad. Side A	Emiss. Side A	Therm. Rad. Side B	Emiss. Side B	Scope
1	Yes	0.7	No		FULL
2	Yes	1.0	No		FULL
3	Yes	0.8	No		FULL
4	Yes	0.3	No		FULL
5	Yes	0.9	No		FULL
6	Yes	0.5	No		FULL

- The radiation scope can be specified for each conductor
  - FULL scope is default – same as GLOBAL in 8.1
  - Example – X-LINE scope means two conductors will see each other only if the attached cells lie along a common line parallel to the x-axis.
  - For mixed scopes, both scopes must be satisfied, e.g.,
    X-PLANE & Y-PLANE – Z-LINE

APPLICATIONS

Ongoing work to look at performance on various scales:

- Detailed model to simulate the drain/dry/fill process as fuel is transferred from the pool to the cask and prepared for storage.
  - Examine thermal performance inside cask to compare to vendor data
- Detailed model of steady state conditions within the cask following storage preparations.
  - Unit cell model of single cask to examine heat transfer to concrete with conservative assumptions for heat transfer to atmosphere.
- Progressively considering simpler representations to decrease run times without sacrificing accuracy relative to the detailed model.
- Future work will model an array of casks to examine atmosphere/building conditions

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SUMMARY

Zachry has used to GOTHIC to analyze spent fuel casks

- Temperature and pressure conditions
- Flow patterns
- Inform design and procedures
- Computationally efficient relative to CFD
- Captures two-phase flow effects for relevant conditions
- Radiation heat transfer, which GOTHIC considers, is a significant contributor to overall performance

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