出國報告(出國類別:開會)

赴美國參加
「2024 年太平洋盆地核能會議」
出國報告

服務機關：核能安全委員會

姓名職稱：核安管制組黃郁仁副研究員

保安應變組賴佳琳技正

派赴地區：美國/愛達荷州

出國期間：113 年 10 月 6 日至 13 日

報告日期：114 年 1 月 8 日

摘要

2024 年第 22 屆太平洋盆地核能會議由美洲核能協會(American Nuclear Society，簡稱 ANS)與太平洋核能理事會(Pacific Nuclear Council，簡稱 PNC)共同主辦，並由愛達荷國家實驗室(Idaho National Laboratory，簡稱 INL)協辦，會議目的為促進太平洋盆地地區之核能和平用途研究與發展合作，自 1976 年以來已經舉辦 21 次，2024 年輪由美國舉辦。

本次會議主題為「核能可實現淨零碳排世界(Nuclear Enabling a Net-Zero World)」，旨在促進整個環太平洋地區相互交流當前和未來的核能研究與開發活動、管制措施與政策、以及核能產業計畫和項目，目的是使核能發揮更高效能，以期能在全球淨零碳排放的目標上發揮重要作用。

會議邀請環太平洋盆地核能使用國家，本次參與人員主要來自美國之核能相關機構、贊助廠商、學術單位、以及愛達荷國家實驗室，另外有加拿大、英國、法國、印度、中國、日本、韓國及我國等國之政府官員、業界專家、研究學者，參與各項先進技術研發、能源管理至管制政策等不同領域之專題，總計發表約 132 篇技術論文，會議現場並設有約 14 個贊助公司的產品攤位展示。

核能安全委員會(以下簡稱核安會)由黃郁仁副研究員和賴佳琳技正偕同出席，均於技術專題論壇中就各自專業領域發表論文與進行口頭簡報，展現我國對除役過渡階段電廠管制措施與核子事故時民眾防護行動規劃，並在主辦單位安排下參訪愛達荷國家實驗室廠址與實驗室等設施，觀摩該實驗室過去歷史與最新核能技術研發項目。參加本次會議，有助於瞭解目前太平洋盆地核能使用國家之核能發展動態，藉由與各國專家學者交流，可增進與國際間聯繫管道，吸取管制經驗並有助於審視精進我國相關議題能量。

目錄

壹、出國目的

太平洋盆地核能會議((Pacific Basin Nuclear Conference，簡稱 PBNC))為太平洋核能理事會(PNC)主導辦理之國際大型研討會，目的為促進太平洋盆地地區之核能和平用途研究與發展合作，邀請對象為環太平洋盆地核能使用國家，自 1976 年首次於夏威夷檀香山舉辦以來，已辦理 21 次(約每 2 年辦理一次)，這些會議在核能技術研究和開發方面，提供了一個交流討論和資訊分享的平台，對於促進核能和平用途發揮了至關重要的作用。

我國現階段國內有三座核能電廠，陸續進入除役過渡階段，核安會身為輻射安全主管機關，對於核能和平安全使用責無旁貸，對於國際事務之參與及最新研究發展趨勢之涉獵亦為職責之一。

2024 年第 22 屆太平洋盆地核能會議由美洲核能協會(ANS)與太平洋核能理事會(PNC)共同主辦，並由愛達荷國家實驗室(INL)協辦，會議主題為「核能可實現淨零碳排世界」，核安會由黃郁仁副研究員和賴佳琳技正偕同出席，於技術專題中就各自專業領域發表「台灣第一核能發電廠乾式貯存設施安全管制」及「台灣核子事故民眾防護行動規劃」論文 2 篇，並於會議上進行口頭簡報，與各國專家學者交換意見。本次會議也在協辦單位安排下參訪愛達荷國家實驗室，觀摩該實驗室最新核能技術研發項目，本次會議有助於瞭解目前太平洋盆地核能使用國家核能發展現況、最新技術及管制措施等相關議題，藉由與各國專家學者交流，可增進與國際間聯繫管道，吸取管制經驗並有助於審視精進我國相關議題能量。

貳、出國行程

本次出國行程含往返共計 8 日，行程表如表 1:

表 1、本次觀摩行程表

日期	行程內容
10 月 6 日	去程 (桃園國際機場→美國西雅圖機場→愛達荷州愛達荷福爾斯)
10 月 7-10 日	參加第 2024 年太平洋盆地核能會議
10 月 11-13 日	返程 (愛達荷州愛達荷福爾斯→美國西雅圖機場→桃園國際機場)

參、過程紀要

2024 年第 22 屆太平洋盆地核能會議(簡稱 PBNC 2024)在美國愛達荷州舉辦，旨在促進整個環太平洋地區相互交流當前和未來的核能研究與開發活動、管制措施與政策、以及核能產業計畫和項目，目的是使核能發揮更高效能，以期能在全球淨零碳排放的目標上發揮重要作用。

PBNC 2024 會議主題為「核能可實現淨零碳排世界」， 參與人員主要來自美國之核能相關機構、贊助廠商、學術單位、以及愛達荷國家實驗室，另外有英國、法國、印度、中國、日本、韓國及我國等各國之政府官員、業界專家、研究學者，參與各項先進技術研發、能源管理至管制政策等不同領域之專題，總計發表約 132 篇技術論文，會議現場並設有約 14 個贊助公司的產品攤位展示。

會議議程分為專題研討論壇、技術議題論壇(含特別論壇)、以及愛達荷國家實驗室參訪(議程詳附件一)，其中專題研討論壇由全體人員共同參與，技術議題論壇則依據不同子議題分組進行，以下就本次參與部分摘述如下：

一、專題研討論壇(Plenary Session)

10 月 8 日上午開幕式及 10 月 9 日上午都是專題研討論壇，共計四場次：

(一) 開幕式：淨零世界中核能的角色(Nuclear in a Net Zero World)

本場次專題研討論壇同樣為開幕式，由來自世界各地的核能領域重要人士，分享他們對於核電如何在未來影響淨零世界的看法，重要出席人員包括 PBNC 2024 主席 Corey McDaniel 博士(Kiewit Nuclear Solutions 公司負責人，同時也是 PNC 主席及本場次會議主持人)、PBNC 2024 榮譽主席 John Wagner 博士(愛達荷國家實驗室負責人)、美國能源部核能辦公室代理助理部長 Michael Goff 博士、奧本海默計畫(Oppenheimer Project)創始人及首席執行長 Charles Oppenheimer(「原子彈之父」羅伯特．奧本海默孫子)、加拿大原子能有限公司總監 Rob Whittleston、日本原子力研究開發機構(Japan Atomic Energy Agency; 簡稱 JAEA)國際事務及福島研發執行長船木健太郎、韓國原子能研究所(Korea Atomic Energy Research Institute; 簡稱 KAERI)核子政策與策略資深副總裁 Chae Young Lim 博士。

所謂的淨零(或稱淨零碳排)，所指意義是儘可能將溫室氣體的排放量降

至最低、並透過碳中和等手段，減輕對地球環境可能造成的影響，包括溫室效應、全球暖化等。由於傳統能源及化學物質的大量使用，地球的溫室效應問題日趨嚴重。聯合國為此召開多次國際會議，謀求解決之道，並進行全球性的碳排管制在 2015 年聯合國氣候峰會上的《巴黎氣候協定》，數百個國家簽署同意在 2050 年前達到碳中和的目標，並在各自國家紛紛推動淨零排放相關立法，確保此一共同目標可以達成。共同維護地球生態環境，是每一個文明國家無可迴避的責任，我國雖非聯合國成員，推動淨零碳排，減少因使用能源而產生的污染，亦是責無旁貸，前總統蔡英文在 2021 年世界地球日(4 月 22 日)，宣示台灣 2050 達到淨零排放的決心，隔年(2022 年)國發會並協同各部會提出「台灣 2050 淨零排放路徑」，內容包含 12 項關鍵戰略，橫跨能源、交通、資源循環、碳匯、金融與綠生活，並針對各項戰略提出各部會中長期執行計畫方針，展現了我國跟隨全球腳步，實現淨零碳排目標的決心。而本次 PBNC 會議主題「核能可實現淨零碳排世界」，其宗旨就是期望透過核能開發利用，達到此一永續發展目標。

在本專題研討論壇中，會議主席 John Wagner 提到世界正面臨前所未有的能源挑戰，無論是氣候變遷、人工智慧資料中心高速成長、各國製造業的蓬勃發展，都帶動了對電需求的急劇增長，因此尋找清潔(低碳排)、可靠、穩定供應、並且符合成本預算的能源，已成為全球共識。後續在日本的演說中也提到：「應對氣候變遷是一項全球性挑戰，任何一個國家都無法單獨應對。」國際間勢必攜手合作，唯有透過全球核能界團結一致，核能發展才能在未來能源市場中佔有一席之地。PBNC 2024 的核心共識，亦是凝聚全球核能領域重要推廣人士向心力，共同推動核能發展，以滿足未來世界對能源亦發強勁的需求。

接續來自美國、加拿大、日本的專家學者在其演說中提到了各自國內目前的核能發展，以及如何透過核能產業達到淨零碳排的目標，而幾乎每位演講者的演說都提到了在 2023 年的聯合國氣候變遷大會(簡稱 COP 28)中，由多國簽署所提出的核能聯合宣言，該宣言主旨是希望透過推動淨零核(Net Zero Nuclear)行動倡議，提升核能技術與工業發展，使核能成為各國官方認

可的清潔能源，在達到淨零碳排的同時，也推動核能工業的發展，並期望在2050 年將全球核能產能和發電量提高至現有的 3 倍(從 100GW 至 300GW)，俾最終能達到全球邁向 2050 淨零排放的遠大目標。

(二) 核能工業界如何達到核能淨零的目標(Industry Achieving Nuclear Net Zero)

本場次專題研討論壇，是由來自工業界的世界領導人，從核子反應器、供應商、建築和研究等不同角度，對於部署新核電以實現淨零未來方面所發揮的作用提供觀點。重要出席人員包括了ANS 主席 Lisa Marshall 博士(同時也是本場次會議主持人)、ANS 執行董事及首席執行長 Craig H. Piercy、世界核能學會(World Nuclear Association；簡稱 WNA)總幹事 Sama Bilbao y León 博士、美國 TerraPower 公司總裁及首席執行長 Chris Levesque、美國 Curtiss-Wright 公司核能部門副總裁 Gary Wolski、日本原子工業論壇(Japan Atomic Industrial Forum，簡稱 JAIF)資深常務董事植武明仁、美國 Amentum 公司(美國政府和商業服務承包商)副總裁 Eric Knox。

本場次主要邀請到多為業界人士，來自各國核能產業的領導者共同分享了對於未來核能的憧憬及遠大目標，包括建設新的核子反應器、延長原有反應器運轉年限、以及開展新技術(小型模組化反應器、核融合技術、脫碳技術、鈉冷卻快中子反應器)等，但也同時提到了想要達成這些目標，需要穩定的資金、完整的供應鏈、健全的投資回收體系、該國監管機關的核准，以及最重要的--民眾支持，才能做到。引用日本原子工業論壇資深常務董事植武明仁的演說中所提到：「民眾對核能的支持，是實現核淨零的最關鍵因素。」對於曾在 2011 年發生福島事故，導致從 2011 年到 2014 年，核電佔全國總發電量比例從原有的 30%降至零的日本來說，重新取得民眾支持無疑是沉重且艱鉅的挑戰。民眾是否支持核能產業發展，間接卻有力地影響了一國的核能產業政策，無論是能源方案、或是相關監管法規制定，都和民眾對於使用核能的看法息息相關，監管機關的角色，在專業中立之餘，亦難以和民眾看法完全切割，這也是每個國家在發展核能必然遇到的挑戰和不可迴避的課題。

另一個被提到的是核電廠的安全問題，事實上，核能發展這幾年最為關切的也就是安全議題，民眾對核子事故的後果恐懼，進而發展成抵制核能，

如果無法解決安全問題，就沒辦法將核能發展推上新的高度。此外，近年來國際間亦發白熱化的戰爭情勢也讓人擔憂，烏克蘭札波羅熱核電廠的案例讓人恐懼核電廠成為戰爭攻擊的目標，這是新興的核能安全議題，但同樣需要被正視和妥善因應。

除此之外，對於核能工業發展而言，一個強大的供應鏈是必不可少的。本場次幾乎每位業界代表，都提到了具備穩定堅固又有彈性的供應鏈的重要性，良好的供應鏈由一群健康的供應商組成，特點是對其技術、人力資源和製造設施進行持續投資，並且核能電廠經營者能夠按時、按預算執行營運；唯有穩定的金流，才能支撐一整個產業，這點就算套用到其他產業亦適用。核能產業目前面對的問題，是難以找到企業願意投資、提供穩定資金來源，而這又和前面所述的民眾支持議題息息相關，看不見明確的核能前景，幾乎沒有任何企業敢貿然進行投資。

美國能源部核能辦公室代理助理部長 Michael Goff 博士和 ANS 執行董事及首席執行長 Craig H. Piercy 的演說中，均提到目前美國核能工業如何致力於尋求發展機會，倚賴其不只能帶來穩定的能源供應、滿足用電需求，同時達到淨零碳排氣候目標，也能創造大量長期穩定的就業機會。Michael Goff 博士提到，目前的核能工業發展策略，除確保現有運轉中核子反應器維持運作之外，也考慮了重啟部分過去已關閉的反應器，包括 2022 年 5 月停機的密西根州 Palisades 核電廠、以及賓州三哩島核電廠的 1 號機組，都有機會在美國核能管制委員會核准後重返運轉。此外，美國也投注資金研發小型模組化反應器(Small Modular Reactor，簡稱 SMR)，在經過長達 10 年的核子反應器關閉浪潮後，美國聯邦與州政府對重振核能出現了不斷增長的跨黨派支持，這對於該國的核能工業而言是個嶄新的契機。目前美國也正致力於培育反應器操作人才，透過和大學合作，設計完整的訓練課程並建立實習生專案，以滿足未來增長的人力之需。

(三) 核能淨零和能源安全之間的平衡(Balancing Nuclear Net Zero with Energy Security)

本場次專題研討論壇，是由來自美國政府、參議員、工業界代表，從核

能淨零政策、電力公司、燃料廠家和投資者等不同角度，對於核能淨零和能源安全之間的平衡提供觀點。重要出席人員包括 PBNC 2024 主席 Corey McDaniel 博士(同時也是本場次會議主持人)、美國參議員 James Risch、美國 Orano 公司執行長 Jean-Lus Palayer、法國 Framatome 燃料廠家經理 Norman Garner、前韓國核能協會總裁 Jaejoo Ha 及能源基金投資者 Scott Nolan。

本場次主持人 Corey McDaniel 博士同時也是 Kiewit Nuclear Solutions (簡稱 KNS)公司負責人，他首先介紹了該公司核燃料與進步型反應器部門，在美國核能電廠業務與淨零推動中所扮演的角色，其核能事業拓展於全美範圍，具有經驗管理團隊，並注重品質與安全，領域涉及各核能電廠、進步型與小型模組化反應器、核燃料公司及其供應鏈，近期合作計畫包含愛達荷國家實驗室複合型核物料與燃料(Material and Fuels Complex，簡稱 MFC)的核燃料熱室實驗設施(Hot Fuel Examination Facility ，簡稱 HFEF)，並提到新墨西哥州的 Kairos 電力公司開始興建熔鹽製成設施(Salt Processing Facility)，以生產熔鹽式反應器之熔鹽冷卻劑，以及田納西州刻正規劃興建離心式濃縮鈾燃料設施等其他進步型反應器，以達到政府淨零政策。

美國 Orano 公司執行長 Jean-Lus Palayer 的演說中介紹了該公司在美國核能電廠業務與淨零推動所扮演的角色，包含用過燃料與低放射性廢棄物(Greater than Class C, 簡稱 GTCC)傳送護箱運輸、INL 廢料處理設施、標靶藥物製成設施，以及乾貯系統製造設施。執行長並提到美國核燃料循環所面臨的挑戰，目前美國核設施每年對於鈾燃料供給僅 5 百萬 SWU(Seperative work unit，分離功單位)、需求卻高達 1 千 5 百萬 SWU，另乾貯設施供需達平衡為每年貯存 2200 噸用過燃料，若想達成 2050 年提升 3 倍核能裝置容量的目標，現階段鈾燃料製程與乾貯設施容量明顯不足。為解決此問題，Orano 公司預定於田納西橡樹嶺規劃 Project IKE Enrichment 廠址，興建離心式濃縮鈾燃料設施，並與在地燃料循環廠家設施合作，提升鈾燃料再利用率，拓展法國母公司鈾濃縮與燃料循環量能，同時配合美國能源部淨零政策，以提供進步型反應器足夠的燃料。

法國 Framatome 燃料廠家經理 Norman Garner 的演說中介紹了其公司如

何藉由提升鈾燃料濃縮度，從輕水式反應器使用的低濃縮鈾(low enriched uranium，簡稱 LEU)燃料(鈾濃縮度 0.72~5%)到 LEU+燃料(鈾濃縮度 5~10%)，甚至是進步型反應器所使用的高純度低濃縮鈾(high-assay low enriched uranium，簡稱 HALEU)燃料(鈾濃縮度 10~20%)，來提升燃料使用效能。在美國輕水式反應器被限制鈾濃縮度不超過 4.95%之 LEU 燃料，若改使用濃縮度較高的 LEU+，可延長燃料週期至 24 個月，且高燃耗可增加燃料使用率，減少燃料退出與乾貯使用。另濃縮度更高的 HALEU 燃料可用於進步型反應器，來增加氫能產出與經濟效益。此外，燃料設計變更還需配合調整燃料循環設計、燃料製成、濃縮鈾供應、用過燃料池格架升級、反應器運轉及用過燃料管理等安全限值，未來 LEU+燃料設計將提交予美國核管會審查，以期能使用於全美的輕水式反應器。

前韓國核能協會總裁 Jaejoo Ha 於演說中介紹核能對於未來能源發展與安全所面臨的挑戰，一開始就先提到了發展人工智慧(Artificial Intelligence,簡稱 AI)數據中心所需要的電能估計於 2026 年會增加 1 倍，而每解答 1 個 chat GPT 的問題約等於充滿 1 台智慧型手機的電量，因此核能與再生能源是未來解決淨零碳排的首要方式，但反觀前面所提 2050 年核能要增加 3 倍裝置容量至 15%，屆時再生能源可能已達 70%，如此不用等核能發展，再生能源早已滿足人類供電需求，面對這樣的挑戰，更要積極去推動核能。他認為燃料穩定供給(包含石化、再生能源、核能與核燃料循環)、穩定的電網輸送及合理的價格將是三大重要關鍵，若核能裝置容量增加，將面臨浮動負載(非基載)需求，而韓國季節性電力需求差異較大，通常是夏天或冬天才需額外用電，現有的再生能源裝置容量可足以應付春季供電需求，但分享型的再生能源裝置則不利於電網的穩定性，若將負載追隨的小型模組化反應器與再生能源結合，則可提供穩定的氫能給再生能源裝置使用。此外應經由成本分析，如再生能源與後備能源如天然氣、小模組化反應器、氫能等選項，與核能進行比對評估其經濟效益，若確實有經濟效益，再生能源也可搭配小模組化反應器作為後備能源。

(四) 核融合和核淨零：核融合的應用--我們離目標有多近？(Fusion and Nuclear Net Zero: Practical Fusion Energy--How Close Are We?)

實用核融合能源的前景一直是當今炙手可熱的研究主題和新聞話題，本場次專題研討論壇，即是由來自各國相關領域的學術與研究單位代表，從政府學術與工業界研究單位等不同角度，對於核融合所面臨的挑戰、潛在應用和未來發展提供觀點。重要出席人員包括 ANS 主席 Lisa Marshall 博士(同時為本場次會議主持人) 、加拿大核能實驗室(Canadian Nuclear Laboratory，簡稱 CNL)副主席 Darren Radford 博士、韓國核融合能源研究院博 Si-Woo Yoon 博士、日本核融合科學與技術研究院副處長 Shunsuke Ide 博士、美國國家工程院 (National Academy of Engineering，簡稱 NAE)處長 Kathy McCarthy 博士、及美國仿星器核融合公司 Type One Energy Group 副主席 Brad Nelson。

加拿大核能實驗室副主席 Darren Radford 博士於演說中介紹了該實驗室在核融合和核淨零推動所扮演的角色，並介紹加拿大核能發展與進步型重水式反應器(Advanced CANDO)的研究歷程，其研究領域涉及加拿大重水式反應器與輕水式反應器、小模組化反應器建置、進步型核燃料製成與氫能科學，並提升放射性同位素的生醫技術及生態環境保護。對於目前核融合應用的時程規劃，Darren Radford 博士認為各國研究團隊現階段都有計畫興建新的實驗設施，但仍需要特殊核燃料循環及非核融合能源技術支援，CNL 於今年啟動 20 億美金新計畫支持核融合研究發展，並與日本、英國研究單位合作，預定 2040 年實現商轉目標。

韓國核融合能源研究院 Si-Woo Yoon 博士的演說中介紹了韓國核融合研究現況與加速商轉策略，並介紹韓國超導體托卡馬克進步型研究用反應器(Korea Superconducting Tokamak Advanced Research, 簡稱 KSTAR)的研究歷程。KSTAR 參與國際熱核融合實驗反應器(International Thermonuclear Experimental Reactor，簡稱 ITER)研究計畫，於 2007 年興建完成，2008 年初期實驗確認電漿體(first plasma)，並持續提升改善設備以確保能穩定運轉。KSTAR 能高效率穩定運轉的關鍵因素為維持電漿體的對稱性、反應器內控制線圈、中子束脈衝效率及技術分析。目前美國、歐盟、日本、韓國、中國大陸、俄羅斯與

印度預計合作興建ITER，並於2024年完成電源變壓器與真空腔體安裝工程。

美國國家工程院處長 Kathy McCarthy 博士於演說中介紹興建中的國際熱核融合實驗反應器(ITER)，目前面臨三個挑戰，第一是產生自發性的核融合能源，第二是材料必須要在核融合嚴苛的環境下存活，第三是燃料自給自足提供持續性的核融合反應。今年針對興建 ITER 計畫提出新的時程規劃、經費預估及更新設備技術，預定 2034 開始研究運轉、2035 年開始模擬氫同位素 D-D 運轉及 2039 年 D-T 運轉。

美國仿星器核融合公司 Type One Energy Group 副主席 Brad Nelson 說明核融合可重現與太陽相同的反應，提供足夠高密度與溫度的熱中子電漿，並可將燃料原子核相互融合時所產生的巨大能量作為熱能，有效利用於發電等領域。該公司近期獲得美國能源部核融合里程碑發展計畫，並開始著手設計新型核融合反應器，其興建位置選址於田納西州除役的 Bull Run 火力電廠。

在後續開放討論過程中，主題圍繞著核能淨零或新技術的發展能否用更便宜的方式興建開發，會場也有民眾提問質疑當初發生三哩島事故時，核能工業界一再保證要強化改善安全，但如今卻只討論節省成本以及如何與再生能源競爭，主席也解釋這些節省成本的建議只是提議，並不見得會通過美國管制單位的同意。

全球正面臨前所未有的能源挑戰，無論是氣候變遷、人工智慧資料中心高速成長、各國製造業的蓬勃發展，都帶動了對電需求的急劇增長，因此尋找淨零碳排、安全可靠、供應穩定、並且符合成本預算的能源，已成為全球共識。達到淨零碳排的目標是一項全球性挑戰，任何一個國家都無法單獨應對，國際間勢必攜手合作，本次會議研討主議題「核能可實現淨零碳排世界」，即是希望凝聚全球核能領域重要推廣人士向心力，共同推動核能發展成為未來能源市場供電主流，以滿足未來世界對能源亦發強勁的需求。

本次會議並宣布了下一屆 PBNC 預計將於 2026 年 4 月假南韓釜山辦理。

二、技術議題論壇(Technical Sessions)

10 月 8 日下午、10 月 9 日下午、10 月 10 日上午均為技術議題論壇時間，共計 6 場次。PBNC 2024 總計發表約 132 篇技術論文，又依內容屬性分為下列 16 項子議題，並區分為一般論文(上限 10 頁，口頭發表 20 分鐘)和閃電演說(lightning talks，僅 1 頁摘要，口頭發表約 7 分鐘)兩種發表方式，：

一般論文發表議題：

1. 以核能實現淨零排放：永續發展之路(Nuclear Enabling Net Zero: Path to Sustainability)
2. 淨零時代的核能經濟學(Economics of Nuclear Energy in the Net-Zero Era)
3. 透過建模、模擬、人工智慧和機器學習發展先進核能(Advancing Nuclear Energy Through Modeling, Simulation, AI, and Machine Learning)
4. 淨零世界中的核安、保安和監管相容性(Nuclear Safety, Security, and Regulatory Compliance in the Net-Zero World)：
5. 永續能源時代先進反應器的創新(Innovations in Advanced Reactors for Sustainable Energy Generation)
6. 提高性能的燃料循環策略(Fuel Cycle Strategies for Enhanced Performance)
7. 未來屬於核融合：實現永續發電(The Future Is Fusion: Enabling Sustainable Power Generation)
8. 核能：平衡社區與環境(Nuclear Energy: Balancing Communities and the Environment)
9. 核能領域的新興話題(Emerging Topics in Nuclear)

閃電演說議題：

10. 核能系統的電腦模擬研究(In Silico Studies of Nuclear Energy Systems)
11. 核融合能源系統之根基(Underpinning Fusion Energy Systems)
12. 先進反應器部署(Advanced Reactor Deployment)
13. 從挑戰到機會－探索社區、環境與防止核擴散(From Challenges to Opportunities--Navigating Communities, Environment, and Nonproliferation)
14. 先進核能：性能、特徵和輻射照射後檢查(Advancing Nuclear Energy:

Capabilities, Characterization, and Post-Irradiation Examination)

15. 先進核能的建模與模擬(Modeling and Simulation Advancing Nuclear Energy)
16. 核子燃料和核子材料(Nuclear Fuels and Materials)

其中議題又主要聚焦於「透過建模、模擬、人工智慧和機器學習發展先進核能」、「淨零世界中的核安、保安和監管相容性」、「永續能源時代先進反應器的創新」等主題論文量最多；此外本次論文大多數(約佔 85%)為協辦單位愛達荷國家實驗室發表，顯示該實驗室於核能產業之高度研發能量能。

本次技術議題論壇共計 6 場次，每場次約有 5 個討論室同時進行，探討不同子議題並進行論文口頭發表，由與會人員自行選擇參加。考量核安會職責為輻射災害防救及核安監管作業，本次多擇「淨零世界中的核安、保安和監管相容性」場次參與，賴員及黃員亦是於該子議題下進行論文發表，以下就參與場次收穫擇要說明如下：

戰爭對核電廠造成的影響，是近年國際上相當關注的議題，在印度弗萊明大學所發表「確保核電廠的安全，在充滿衝突的世界中實現淨零排放(Ensuring Security of Nuclear Plants, enabling Net Zero in a Conflict-Ridden World)」論文中提到國際間日益濃烈的戰爭煙硝味可能對核電廠所造成危害的擔憂，文中並提到中國對台灣的侵略意圖、和南北韓、以色列對伊朗等，同為緊張局勢地區之一，文中除提出俄羅斯入侵烏克蘭並接管了札波羅熱核電廠，並在核電廠周遭發生激烈戰鬥，可能嚴重削弱民眾對核能的支持(基於擔憂放射性物質外釋和對核子武器的恐懼)，並會對建設中的核能電廠造成建設延誤、成本超支等挑戰，並產生不利影響，文中並分析了國際公約和雙邊協定對於核電廠不應列為合法軍事攻擊目標的約束力。

核能的應用，首重安全，而核能安全並無國界之分，任何國家一旦發生核子意外事故，不但危及人民生命財產的安全，也必對其他國家的核能發展發生深遠的影響。多年來國際原子能總署及其他國際性核能組織團體，均致力於國際核能合作的推展，核安會身為輻射災害防救應變主責單位，應秉持「核能無國界」的認知，繼續加強技術交流合作，提昇核能科技水準，以增進核能應用之安全，並

持續關注國際戰爭情勢，研擬境外核災潛勢並預備應對作為。

人工智慧和機器學習核能產業的應用也是這次會議的熱門論文主題之一，顯示這些先進運算工具和技術在未來可能大幅改變核電相關產業結構，其中人工智慧是全球發展最快的技術之一，透過提供對核設施設計和營運過程中產生的大量數據的洞察理解和分析，能增強決策流程，因此核能產業界對研究和使用人工智慧技術來提高營運績效和降低營運風險越來越感興趣。目前，人工智慧和機器學習研究主要在反應器系統設計分析（如故障事故預測）、核子風險分析（如核電廠安全和保安評估）以及核電廠運作維護（如預測性維護）等領域進行，本次會議相關論文彙整如下：

- 在 INL 所提出的「核電廠引入人工智慧的考慮因素(Considerations for Introducing Artificial Intelligence into Nuclear Power Plant)」論文中，提出了應用人工智慧與機器學習於核能產業需審慎考慮的因素，包括在技術操作上可能會遇到的問題(如資通安全和資料隱私)、在商業端是否符合成本效益、利害關係人是否做好轉型準備(包括監管端的準備)、以及終端使用者的接受度等等，並提出建議的解決方案。另外在愛達荷州立大學所提出的「核設施安全應用移動機器人技術綜述(A Review of Mobile Robot Technology for Security Applications at Nuclear Facilities)」中，也提出研發狗型機器人在廠內人機共享環境中進行基礎設施安全和遠端檢查的技術，以降低電廠的營運維護勞動力成本。
- 加碼實業公司(Gamma Reality Inc.)提出的「機器人自主 3D 放射線測繪可有效監控下一代反應器(Autonomous 3D Radiation Mapping on Robots for Efficient Monitoring of Next Generation Reactors)」論文中，則提出了使用先進機器人並整合式數位控制、操作和資料管理系統來整合廠內輻射劑量率監測的技術，可降低目前核電廠內各區域定期需要進行的輻射劑量率監測調查、並整合跨時間和空間關聯比較數據的人力需求，也可大幅降低人為錯誤發生率和人員遭受輻射曝露風險機率。
- INL 在「遠端核電廠運作：因應大眾認知中的機會與挑戰(Remote

Nuclear Power Plant Operation: Navigating the Opportunities and Challenges in Public Perception)」一文中提到了遠端操作先進核子反應器的概念，遠端操作可以大幅降低監控和操作成本，特別是同時遠端控制許多地理位置分散的反應器。事實上，遠端操作的概念已經多次被提出，目前該研究領域的努力重點是確保該策略在技術和監管上可行，而本文主要著重於社會的接受度，文中從多角度分析了民眾想法背後的決定和影響因素、以及如何取得大眾的認可，並強調民眾認知和社會許可，將會是新技術應用於核子反應器相關策略時能否成功的決定性因素。

- 另一篇同樣為 INL 所提出的論文「微反應器遠端操作風險分析(Risk Analysis for Remote Operation of Microreactors)」則著重於遠端操作的風險，提出微反應器有潛力用於微型電網、農村和偏遠地區或緊急應變應用，並能取代柴油發電機等化石燃料，實現永續能源發電。文中並提到雖然遠端操作在其他能源工業發電控制系統很常見，但尚未在核能界採用，主因是存在許多感知和實際風險，這些風險主要涉及遠端操控必須增加遠端通訊網路以及數據和控制認證系統，而這些變化可能會造成網路風險，因此必須列入評估並提出解決方案，才能滿足未來對遠端操作的使用需求。

綜上，新技術的進步將推動核能產業的創新，人工智慧和機器學習的快速發展，可顯著提高電廠營運和運作效率，從而節省維護成本，在可預見的未來勢必會被導入核能產業之中，而這是否會影響目前對於核能產業的監管方式、與現行法規有無牴觸、甚至是否須因此調整目前的監管做法，亦是我國必須與時俱進面對並解決的問題。

除此之外，人工智慧和機器學習可以簡化複雜問題並產出有效決策，亦可思考能否善用此一優點，將人工智慧和機器學習引進核安監管作業中，提升監管效率。本次論文亦有涉獵到將相關技術引進管制作業的議題，例如由 INL 提出的「探討大型語言模型在核電廠特定用例決策中的功效(Exploring the Efficacy of LLMs in Decision-Making for a Specific Use Case in Nuclear Power Plants)」論文中，探

討了使用常見的人工智慧工具--大型語言模型（large language model，簡稱 LLM）來對電廠內的事故報告(condition report)進行分類，以區別是屬於有害狀況、非有害狀況、或重大有害狀況，而這以往是靠人力在進行分類的。LLM 是現今常使用的人工智慧工具，透過模仿人腦神經元的神經網絡，對於目標需求在接受過互聯網、圖書館資料和其他數十億份文件的訓練後，LLM 可以識別、彙整、翻譯、預測和生成目標所需的內容。

本次會議中也提到了美國核能管制委員會(Nuclear Regulatory Commission，簡稱 NRC) 於 2023 年 5 月所頒布的 NUREG-2261 號文件，該文件係因應人工智慧的快速發展，美國核管會意識到，未來人工智慧廣泛應用於核能產業界必然勢不可擋，從而制定了「人工智慧策略計畫：2023-2027 年度(Artificial Intelligence Strategic Plan: Fiscal Years 2023-2027)」。該文件中賦予了人工智慧的具體定義，並聚焦於自然語言處理、機器學習、深度學習等人工智慧子專業領域，考量到其中可能包含 NRC 先前未曾審查和評估的各種演算法和應用範例，為致力於繼續跟上技術創新的步伐，以確保在未來的核能作業監管中安全可靠地使用人工智慧，爰提出此份文件。此文件提出五大目標：(1)確保 NRC 為監管決策做好準備；(2)建立審查人工智慧應用的組織框架；(3)加強和擴大人工智慧合作夥伴關係；(4)培養精通人工智慧的人力資源；(5)建立案例資料庫並進行分析。總體目標是確保監管機關內部做好準備，具備能力且能有效率地審查和評估人工智慧應用。

本次會議所發表論文，多次提及應用人工智慧與機器學習於核能產業之各項創新科技，新技術的快速發展將推動核能產業的創新，可達到顯著節省核電廠運營和維護成本，在可預見的未來勢必會被導入產業界及商業化，而這是否會影響目前對於核能產業的監管方式、與現行法規有無牴觸、甚至是否須因此調整目前的監管做法，亦是我國必須與時俱進面對的問題。本次會議所提出論文雖多處於研究發展過程，尚未能實際商業化並落實應用，然身為我國核安管制機構的一員，亦應持續關注世界趨勢，強化個人專業知能，以預為因應未來管制措施可能的調整；相對的，亦可思考是否能將人工智慧和機器學習引進核安監管作業中，以提升監管效率。

核安會黃郁仁副研究員於 10 月 9 日發表「Experience on Regulating Shutdown Cooling System of RHR during Chinshan Nuclear Power Plant Decommissioning in Taiwan」論文(詳附件 2)，分享我國核能一廠兩部機組在運轉執照屆期進入除役過渡階段的管制作業，過程如圖 1。

由於核能一廠在進入除役期間，反應器爐心仍有用過核子燃料，台電公司提出一項安全分析報告，向核安會申請停轉備用運轉餘熱移除系統，改以用過燃料池冷卻系統和反應器水淨化系統作為替代爐心冷卻措施。台電公司參考世界核能發電協會的類似經驗，遵循美國核管會的技術文件(TSTF-566)，並制定有特殊程序書 STP-109-01，以供運轉人員遵循。同時，管制單位已完成相關審查作業，包括技術規範、試驗及監測參數、安全評估與異常應變等。

核安會為進行相關安全評估，除審查台電公司所使用之熱傳公式外，亦針對台電公司利用 RELAP-5 程式平行驗證與評估爐心熱水流型態及爐心上方至爐心底部溫度佐證數據，要求台電公司進行爐心替代冷卻測試及實際量測機組爐水溫度，以作為未來的審查安全分析報告和後續管制作為之依據。核安會在台電公司執行特殊程序書 STP-109-01 爐心替代冷卻測試前，要求評估發生喪失用過燃料池冷卻系統、喪失外電、電廠全黑，以及爐心與用過燃料池水位下降等因應措施，經核安會審查確認餘熱移除系統與新增用過燃料池冷卻與補水系統能於發生事故期間內恢復可用，以確保測試期間相關安全系統設備之多重性、多樣性與深度防禦。核安會並要求台電公司執行爐心替代冷卻測試期間，於反應器爐穴安裝移動式溫度儀器、寬程中子監測系統(Wide Range Neutron Monitor, 簡稱 WRNM)核儀乾管安裝爐心溫度計，並利用既有爐心與用過燃料池系統既有水位、溫度儀器執行實際量測機組爐水溫度。經比對安全評估結果，反應器爐穴與爐心溫度與實際量測結果相近，並考量在環境中散失熱量與儀器不準度，且替代冷卻測試期間，反應器與用過燃料池溫度均小於技術規範限值(<51.6^{0}C)。在電廠執行前述測試期間，核安會亦派員進行現場查證替代冷卻的用過燃料池冷卻水泵與熱交換器現場

設備狀況，並於控制室查證運轉人員對於反應器與用過燃料池的水位、溫度參數監控與抄表紀錄，確認反應器水和用過燃料池水溫度與送審安全評估報告之評估結果與數據正確性以及替代爐心餘熱冷卻設備可用性，以符合規範要求。另核安會亦要求台電公司回饋運轉人員訓練與修正模擬器設定，並依美國核管會除役視察手冊 IMC-2561，對用過燃料池冷卻系統維護測試作業進行視察，以確保除役期間公眾健康與環境安全。

核安會賴佳琳技正於 10 月 10 日發表「The Public Protective Action Guides for Nuclear Emergency in Taiwan」論文(詳附件 3)，介紹台灣的核子事故民眾防護行動應變機制，當核子事故惡化至有放射性物質外釋時，即時正確執行民眾防護行動，能有效降低因輻射曝露導致的機率效應發生機率、並減輕確定效應造成的影響，以維民眾生命健康安全，演說過程如圖 2。

核安會在 2005 年(時為行政院原子能委員會)發布「核子事故民眾防護行動規範」，採用干預基準(intervention level)的概念來執行相對應防護措施，並透過劑量評估系統來計算所需的可減免劑量和預期輻射劑量；然而這套機制在 2011 年日本福島事故發生時，在執行上遇到重大困難，原因是劑量評估系統所需的輻射源項及氣象資料等資訊，在事故混亂的狀況下無法即時取得，從而延誤廠外應變單位做出相關民眾防護決策的寶貴時間。

有鑒於此，我國參考日本福島事故教訓與國際相關文獻建議，採納了緊急行動基準(Emergency Action Level；簡稱 EAL)和操作干預基準(Operational Intervention Level；簡稱 OIL)的概念，將之納入民眾防護行動執行時機的整體判定機制內，並制定相關法規與程序書，以完善我國核子事故民眾防護應變整備量能。

在報告完畢後，現場人員對於我國對核子事故發生時民眾防護的努力給予肯定，並交流了在執行上常遇到的困難，例如透過宣導和辦理園遊會等相關活動，來提升民眾對於輻射的認識、降低不必要的恐慌等，並詢問未來若我國續用核能，對於未來新核能時代的發展下，民眾防護行動是否會有更新的規劃。我方回應目前我國政策為 2025 非核家園，屆時將不再有核能發電的相關設施運轉，應變整備規劃將以維持現有應變量能為主；但災害防救規劃本應與時俱進，台灣依舊會依據實務現況和國際情勢進行滾動調整，以確保民眾安全。

圖 1 黃郁仁副研究員口頭發表過程

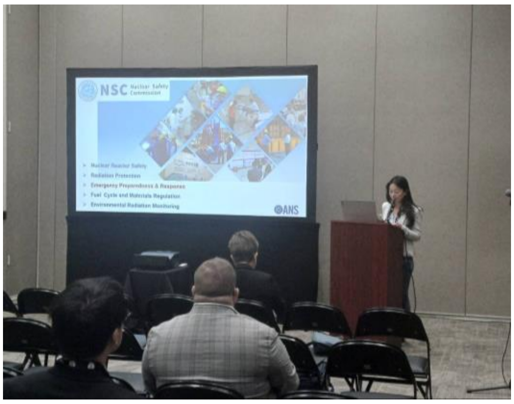

圖 2 賴佳琳技正口頭發表過程

三、特別論壇(Special Sessions)

針對值得單獨提出討論的幾項議題，大會於技術論壇時間召開特別論壇加以討論，該場次中無論文發表，而是針對議題主題，邀請 4-5 位相關來賓，採用主持人提出開放式問題、來賓回應的方式，來激盪觀眾對此一議題的了解，並激發討論。本次特別論壇所探討到的議題如下：

(一) 建設核淨零：經驗教訓與未來的最佳實踐 (Building Nuclear Net Zero: Lessons Learned and Best Practices Going Forward)

在 COP28 會議上所發起的淨零核倡議，對全球核能產業無疑掀起激勵的巨大浪潮，本場次論壇邀請到多國核能產業界的來賓，分享他們對於擴大核電容量的計劃(包括興建新核電廠、沿用舊有核電廠、培育核能產業人才)，並討論如何將淨零碳排的政策具體落實到核能產業中。來賓們於會議中介紹了擴大核能規模的機會、並提出邁向淨零碳排必須克服的多重挑戰和障礙，以及實現淨零核倡議這個雄心壯志所需的方法。參加此一論壇，可更了解淨零核倡議的具體承諾、以及簽署國為落實倡議做出的的部署策略，以了解國際間核能展業的發展趨勢。

(二) 愛達荷州立大學核子技術人員實務培訓 (Hands-on Nuclear Technician Training at Idaho State University)

復興核能產業所需的人才培訓，也是本次大會要推展的目標之一，在世界核能復甦跡象日益明朗之際，許多國家或組織已注意到面臨核能相關人才

供需瓶頸問題，為滿足未來對工程技術人員日益增長的潛在需求，愛達荷州立大學技術學院建立了一個能源系統技術和教育中心（Energy Systems Technology and Education Center，簡稱 ESTEC）提供核設施操作訓練相關的技術證書和學位認證。ESTEC 和在地的能源事業公司和供應商合作，對方提出在進入勞動力市場時所需具備的技能要求，再由 ESTEC 據以開發訓練課程，能源產業範圍包括核能、煤炭、天然氣、再生技術等領域，師資則由公司現任員工、畢業生和未來雇主組成。以核能領域為例，反應器核設施技術員訓練證書課程包括了核安文化、輻射安全、核子材料、燃料循環、手套箱類型和維護、電氣安全和電子、機械系統、工具使用、工業安全、起重機和索具、起重機操作、儀器儀表以及故障排除和維修等課程，並透過課堂授課及實地操作來學習。目前該計畫正陸續招募聘僱更多合作夥伴，包括能源產業公司和技術學院，以擴大畢業生未來可進入的市場規模，這些公司也可藉此計畫確保勞動力需求被滿足，相輔相成建立更穩固的人力供應和技術訓練基礎，相關經驗可作為我國對輻射安全人才培育之參考。

(三)燃煤發電廠在未來能源系統中的作用(Role of Coal Stations in Future Energy Systems)

為達到淨零碳排的目標，全球現存的燃煤發電廠預計將會陸續面臨關廠和除役規劃，在本論壇中提到，這些除役的發電廠可以轉型成為研究用途，進行脫碳、碳捕捉、碳封存等技術研究。所謂的碳捕捉設計，是指捕捉電廠排放的二氧化碳，透過化學方法轉換再利用，或以儲存於地層的方式轉化成固態化合物，所需設備包括吸收塔、脫附塔、微型態測試區、溫室等。在過去幾年中，美國的公用事業、電力公司、各州研究人員一直在共同努力，研究調查此類技術的可行性和落實所需的各種資金設備。來賓也提到，前述技術目前尚處於試驗階段，此類研究成本高昂，需得到不同利害關係人的支持才能取得成功，未來最重要在於規模化以及商業化，使其可以真正落實於現在的電廠技術當中，其經驗亦可作為我國未來精進相關技術之參考。

(四)國家實驗室在核淨零中的作用

綜觀能源開發歷史，核能屬於高度專業的創新產業，相關核能科技不斷推陳出新、反應器也不斷面臨創新革命，因此國家實驗室和核能產業的合作至關重要，由實驗室進行技術研究，並測試商轉可行性，再落實到產業面進行運作和營收，是現階段許多國家的產學合作方式。本場次論壇聚集了來自美國愛達荷國家實驗室、韓國原子能研究所、日本原子能總署、加拿大核子實驗室等來賓，共同分享國家實驗室對實現淨零核未來的重要貢獻。來賓們提到了若想透過核能來達到淨零碳排的目標，國家實驗室的角色更是不可或缺，利用具備的獨特專業知識與人才，促進全球推動能源永續、以及淨零核能的目標，目前尚有許多技術處於研究階段，例如脫碳策略、改進反應器技術以及核電在更廣泛的清潔能源計劃中的作用。參與本場次會議有助於了解目前各國實驗室的突破性研究、先進核子反應器技術的開發、以及公私部門的合作夥伴關係的重要作用。

(五)婦女和多樣性推動核淨零排放(Women and Diversity Driving Nuclear Net Zero)

本論壇特別關注了在核能領域中有影響力的女性群體，她們正在引領社區和世界實現可未來的核能變革，來賓們由核能領域的領先女性組成，並分享了從女性角度出發的各項議題，包括社區和國際參與、實現核淨零倡議的多樣性價值，並討論女性文化如何能夠在核能領域繼續蓬勃發展的最佳實踐方法。近年來國際間特別關注性別多樣化的影響力，我國亦於 1994 年成立中華民國核能學會婦女委員會，聚集國內輻射及核能領域從業女性，互相交流並與民眾溝通，進而促進大眾對輻射民生應用的了解和支持，並持續出席全球核能婦女會（Women in Nuclear Global，簡稱 WiN Global）辦理之相關年會，將我國核能產業的女性力量帶至國際舞台。

四、愛達荷國家實驗室參訪行程

愛達荷國家實驗室是隸屬於美國能源部下屬的頂尖研究機構，主要進行核能研究，美國許多現代核反應器的操作知識均是出自於此，該實驗室目前擁有約7,000 名員工，主要專注於能源、安全與環境領域的創新研究。沿革如下：

- 1949 年成立國家反應器試驗站(National Reactor Testing Station)
- 1977 年改名為愛達荷能源實驗室 (Idaho National Energy Laboratory)
- 1997 年改名為愛達荷國家能源和環境實驗室(Idaho National Energy and Environmental Laboratory)
- 2005 年 2 月 1 日改現名愛達荷國家實驗室(INL)

此次在 ANS 的安排下參訪實驗室廠址以及研究與教育園區，參訪規定包括人員預先遞交申請資料，不接受當日申請，申請資料內容包括個人簡歷、護照資訊等，當日參訪須出示護照換證，參訪過程全程應配戴訪客證，並提醒廠內不得拍照，以及不可穿著短褲、短裙、露趾鞋等，相關規定類似我國核電廠入廠規定。

參訪過程分述如下：

(一) 廠址參訪

本行程安排於 10 月 7 日辦理，實地走訪包括國家歷史地標實驗增殖反應器-I（Experimental Breeder Reactor-I,簡稱 EBR-I）原子博物館、先進測試反應器（Advanced Test Reactor, 簡稱 ATR）以及材料與燃料綜合體（Materials and Fuels Complex, 簡稱 MFC）等設施，實地了解其設施運作狀況，參訪情形整理如下。

1. **實驗增殖反應器-I（EBR-I）原子博物館**

EBR-I 是愛達荷國家實驗室建造的第一座反應器，也是世界上第一座證明可以利用核能發電的反應器。1951 年 12 月 20 日，EBR-I 成功點亮了四個燈泡，證明了科學家費米(Enrico Fermi)的核燃料滋生理論，象徵核能時代的開啟。該設施目前已被改建為博物館，並被列為美國國家歷史地標(US National Historic Landmark)，是個對於核能發電而言具有獨特意義的歷史地點，博物館內展示了早期核反應器設計的機械結構、控制面板及操作技術，還有相關教育

展覽，旨在傳達核能的科學、歷史和未來應用。

2. **先進測試反應器（ATR）**

先進測試反應器是第三代測試反應器，自 1967 年啟用以來，一直在國際原子能機構最強大研究與測試反應器的名單中名列前茅。其特殊的「爪形核心設計（cloverleaf core design）」可允許不同實驗在同一時間進行，使研究效率大幅提高。ATR 可進行超高中子通量測試，適合材料科學研究，特別是在高輻射環境中的性能測試，能在短短數月內模擬材料在商業反應器中數年甚至數十年的中子輻照損傷，這使其成為美國國內外進行材料和燃料輻照實驗的首選設施，對於推動核能研究、材料科學及反應器安全性具有重要作用，其應用範圍包含為核電廠提供新燃料的壽命評估和安全性測試、為航太和國防項目開發特殊材料，例如耐高溫、抗輻射合金，以及提供醫療領域的同位素生產，例如癌症診斷和治療用的放射性藥物。

3. **材料與燃料綜合體（MFC）**

MFC 是美國核能研究與發展的關鍵設施，其功能涵蓋了從新型燃料的輻照後檢測、到生產放射性同位素電源系統（例如為火星探測車提供動力系統）。該綜合體擁有全球最大的惰性熱室，用於安全處理和分析輻射照射後的高放射性材料，以及兩座測試反應器：瞬時測試反應器（Transient Test Reactor, 簡稱 TREAT）和中子攝影反應器（Neutron Radiography Reactor, 簡稱 NRR）。瞬時測試反應器專門用於模擬快中子反應器事故條件，以測試核燃料的極限性能和安全性；中子攝影反應器主要用於進行非破壞性檢測，廣泛應用於航空航太、軍工和核燃料研究。這些設施為核燃料設計、材料性能研究以及太空探索提供了研究上極為關鍵的支援，其研究成果包含航太領域（如「卡西尼號」探測器、「新視野號」探測器）的放射性同位素電源供電系統，這些系統能在極端環境下穩定運行數

十年，或是通過輻照後材料的微觀結構分析，改進下一代反應器燃料設計，提升能源效率與安全性。

(二) 研究與教育園區參訪

本參訪安排於 10 月 10 日下半日，共計參觀人體系統模擬實驗室(Human System Simulation Laboratory，簡稱 HSSL) 、能源系統實驗室(Energy Systems Lab，簡稱 ESL)以及協作計算中心(Collaborative Computing Center，簡稱 C3)等三個地點，紀要如下：

1. **人體系統模擬實驗室(HSSL)**

第一站首先走訪人體系統模擬實驗室，這是 INL 所開發全面高擬真的核能類比與數位監控模擬系統，有別於以往控制室內的實體操控元件，該系統將所有開關、按鈕、儀表、鍵盤等實體控制工具轉換為虛擬的觸控介面，主要可用於進行運轉員訓練、或在新的功能技術實際上線之前先進行安全測試，以隨時掌握運轉員(operator)調度操作過程、以及與核電廠現場互動的關係。這種模擬器的優點是界面配置控制度高，可以依據需求快速調整介面設計，也可用於測試新興技術，例如電廠進行軟體數位升級，此外該系統還可用於驗證核子事故發生時系統是否能進行安全控制，以及找出特定運轉條件下，進行熱與電系統各自獨立運轉調度。

現場由工程師協同參訪人員於監控模擬板面上，實際操作反應器跳脫情境測試，並且展示核電廠反應器、冷卻系統、主蒸汽渦輪機、冷凝器、與發電機等各監控單元警報動作正確性。

2. **能源系統實驗室(LabESL)**

第二站來到的是能源系統實驗室，該實驗室的研究範圍包含實驗室規模的科學研究到實際運作開發，主要包括了三個主題：(1)生物能源研究(Bioenergy Research)；(2)能源儲存和先進車輛(energy storage and advanced vehicles)；(3)能源系統整合(energy systems integration)。

生物能源研究：該實驗室的生物質原料國家用戶設施(The

Biomass Feedstock National User Facility，簡稱 BFNUF)目前是美國國內開發生物能源原料供應系統的研發技術領導者，致力於研究生物質(biomass)的收集、加工和處理，以為國家能源結構的重要組成帶來經濟上可行的乾淨能源效益。介紹人員也提到，生物質原料很容易因天氣、微生物和其他因素而降解(degradation)，這對於能穩定提供水準一致的生物質原料商品是個重大的挑戰，因此該實驗室的研究目標就是在透過了解國內多樣化農業和森林資源的物理和化學特徵，來克服關鍵技術障礙。

能源儲存和先進車輛：目前全球的車輛運輸產業都在面臨重大轉型，包括了新的燃料、新的電池和新的充電系統，各方面都變得更加節能和技術先進，而壽命更長、更安全且更具成本效益的先進電池對於電動車來說至關重要。現場看見 INL 的電池測試中心，該中心可測試從手錶大小的電池到全尺寸汽車電池組的所有產品，也可為插電式電動車等先進車輛提供公正的真實測試。

能源系統整合：其研究一大重點是微電網實驗研究室，微電網測試平台可將風能、太陽能等儲能結合成一個可動態儲存且又易於管理的能源系統，該平台包括有負載與智慧轉換器，其中的轉換器又可主動管理微電網內的電源。這些研究主要可降低未來能源系統相關的技術和經濟風險，該實驗室也提供配置靈活的設施，以進行實驗室和工程規模的研究和測試，以驗證綜合能源系統的商業準備。

3. **協作計算中心(C3)**

最後一站來到協作計算中心，該中心建於 2019 年，當時園區內大量的科學計算衍伸了對高效能運算資源的需求，超級電腦應運而生，該中心目前使用了五台世界級超級計算機，每天約有上千名使用者用來處理複雜的計算問題，包括建模模擬運跑、數據視覺化和人工智慧研究等，使用者範圍不限於 INL 內部人員，還擴展到有合作關係的大學和工業界。每台計算機每天都需要可供應上百個家庭使用的電力，為此該中心也配備了發電機以防電力中斷，並且配備

有高效且強大的冷卻系統。

但實際上，我們所到訪的協作計算中心看起來就像一座圖書館，整棟建築在置放超級電腦以外的部分，被規劃為多個辦公空間、會議室、以及開放的協作空間，供內部團隊進行討論和集思廣益，同時也可出借場地辦理大型會議和活動，整體而言，就像是大學中常看到的圖資中心。

肆、心得與建議

一、心得

(一) 全球正面臨前所未有的能源挑戰，無論是氣候變遷、人工智慧資料中心高速成長、各國製造業的蓬勃發展，都帶動了對電需求的急劇增長，因此尋找淨零碳排、安全可靠、供應穩定、並且符合成本預算的能源，已成為全球共識。達到淨零碳排的目標是一項全球性挑戰，任何一個國家都無法單獨應對，國際間勢必攜手合作，本次會議研討主議題「核能可實現淨零碳排世界(Nuclear Enabling a Net-Zero World)」，即是希望凝聚全球核能領域重要推廣人士向心力，共同推動核能發展成為未來能源市場供電主流，以滿足未來世界對能源亦發強勁的需求。

(二) 本次會議所發表論文，多次提及應用人工智慧與機器學習於核能產業之各項創新科技，新技術的快速發展將推動核能產業的創新，可達到顯著節省核電廠運營和維護成本，在可預見的未來勢必會被導入產業界及商業化，而這是否會影響目前對於核能產業的監管方式、與現行法規有無牴觸、甚至是否須因此調整目前的監管做法，亦是我國必須與時俱進面對的問題。本次會議所提出論文雖多處於研究發展過程，尚未能實際商業化並落實應用，然身為我國核安管制機構的一員，亦應持續關注世界趨勢，強化個人專業知能，以預為因應未來管制措施可能的調整；相對的，亦可思考是否能將人工智慧和機器學習引進核安監管作業中，以提升監管效率。

(三) 在 COP28 會議上所發起的淨零核倡議，對全球核能產業掀起巨大浪潮，許多國家(如美國、加拿大、日本、南韓)均已開始啟動擴大核電容量的計劃(包括興建新核電廠、沿用舊有核電廠、培育核能產業人才等)，並紛紛部署將淨零碳排的政策具體落實到核能產業中。在全球核能復甦日益白熱化之際，許多國家或組織已注意到面臨核能相關人才供需瓶頸問題，並積極著手建立人才培育中心、建立產學合作管道，以因應未來對技術人員日益增長的潛在需求。因應國際趨勢，我國核能界不論管制單

位、台電公司或研究單位均面臨核能人才留才問題，現行台電公司規劃核能電廠除役期程長達 25 年，可適時規劃如何維持國內核電人才量能。

(四) 我國長期面臨特殊且艱困的國際處境，太平洋盆地核能會議係少數可直接參與之國際會議，經過多年與太平洋盆地國家間的交流，已奠定良好的基礎，今後如何在既有的基礎上，增進彼此的合作交流，共同提昇核能科技水準，開拓核能和平用途，實有賴核安會繼續的努力。

二、建議

(一) 由於地球暖化及能源短缺的議題持續發酵，近年來國際能源趨勢對於核能議題態度逐漸轉變，從過往摒棄核能，到最近美國開始增資核能產業、延役舊有機組，日本韓國也都在考量重啟核電的可能性，核安會應以專業獨立監管機關之角度，審慎看待世界能源發展，並持續關注國際趨勢。

(二) 核能的應用，首重安全，而核能安全並無國界之分，任何國家一旦發生核子事故，不但危及人民生命財產安全，也必對其他國家的核能發展產生深遠影響。核安會身為輻射災害防救應變主責單位，應秉持「核能無國界」的認知，繼續加強國際間的交流合作，提昇核能科技水準，以增進核能應用之安全，並持續關注國際戰爭情勢，研擬境外核災潛勢並預備應對作為。

(三) 太平洋盆地核能會議聚集了環太平洋地區核能使用國家，相互交流當前和未來的核能研究與開發活動、以及管制措施與政策，參與本會議除能了解國際核能發展趨勢，亦可強化與鄰近國家間核安管制技術的交流，並能把我國對於核能安全管制、核子事故緊急應變機制等資訊與國際分享，促進我國與太平洋盆地各國交流與學習，建議持續派員出席。

伍、附件

附件 1、2023 年太平洋盆地核能會議日程表

附件 2、黃郁仁副研究員發表論文

附件 3、賴佳琳技正發表論文

American Nuclear Society

Pacific Basin Nuclear Conference 2024 (PBNC) Schedule Timeline

Monday — October 7, 2024

7:00AM **Events**

- Monday: Visit the birthplace of peaceful atomic power; INL Site Tour [REGISTRATION HAS PASSED] . . . . . TBD

2:30PM **Registration and Exhibit Hall Hours**

- Registration/Help Desk open 2:30–6:00PM . . . . . TBD

Tuesday — October 8, 2024

7:00AM **Registration and Exhibit Hall Hours**

- Exhibit open from 7:00AM–4:00PM and 5:00PM-7:00PM . . . . . TBD
- Registration/Help Desk open 7:00AM–4:00PM . . . . . TBD

7:00AM **Breaks and Meals**

- Breakfast . . . . . TBD

8:00AM **Pacific Basin Nuclear Conference 2024 (PBNC) Plenary Sessions**

- Opening Plenary - Nuclear in a Net Zero World . . . . . Arena

10:00AM **Breaks and Meals**

- Networking Break . . . . . TBD

10:30AM **Pacific Basin Nuclear Conference 2024 (PBNC) Plenary Sessions**

- Plenary II - Industry Achieving Nuclear Net Zero . . . . . Arena

12:00PM **Breaks and Meals**

- Attendee Lunch . . . . . TBD

1:00PM **Pacific Basin Nuclear Conference 2024 (PBNC) Technical Sessions**

- Building Nuclear Net Zero: Lessons Learned and Best Practices Going Forward . . . . . Room 2 (Special Sessions)
- Innovations in Advanced Reactors for Sustainable Energy Generation: I . . . . . Room 3
- The Future Is Fusion: Enabling Sustainable Power Generation . . . . . Room 4
- In Silico Studies of Nuclear Energy Systems: Lightning Talks . . . . . Room 5
- Nuclear Enabling Net Zero: Path to Sustainability . . . . . Room 1

2:45PM **Breaks and Meals**

- Networking Break . . . . . TBD

3:15PM **Pacific Basin Nuclear Conference 2024 (PBNC) Technical Sessions**

- Road to COP30 - Brazil: Nuclear Energy's essential role in reaching Net Zero Nuclear - Pathway to a carbon neutral society . . . . . Room 2 (Special Sessions)
- Innovations in Advanced Reactors for Sustainable Energy Generation: II . . . . . Room 4
- Underpinning Fusion Energy Systems: Lightning Talks . . . . . Room 5
- Advancing Nuclear Energy Through Modeling, Simulation, AI, and Machine Learning: I . . . . . Room 1

- Hands-on Nuclear Technician Training at Idaho State University . . . . Room 3

5:00PM **Events**
- Opening Reception . . . . TBD

5:00PM **Registration and Exhibit Hall Hours**
- Exhibit open from 7:00AM–4:00PM and 5:00PM-7:00PM . . . . TBD

Wednesday — October 9, 2024

7:00AM **Registration and Exhibit Hall Hours**
- Exhibit open from 7:00AM–4:00PM and 6:00–10:30PM . . . . TBD
- Registration/Help Desk open 7:00AM–4:00PM . . . . TBD

7:00AM **Breaks and Meals**
- Breakfast . . . . TBD

8:00AM **Pacific Basin Nuclear Conference 2024 (PBNC) Plenary Sessions**
- Plenary III - Balancing Nuclear Net Zero with Energy Security . . . . Arena

10:00AM **Breaks and Meals**
- Networking Break . . . . TBD

10:30AM **Pacific Basin Nuclear Conference 2024 (PBNC) Plenary Sessions**
- Plenary IV - Fusion and Nuclear Net Zero: Practical Fusion Energy – How Close Are We? . . . . Arena

12:00PM **Breaks and Meals**
- Attendee Lunch . . . . TBD

1:00PM **Pacific Basin Nuclear Conference 2024 (PBNC) Technical Sessions**
- Women and Diversity Driving Nuclear Net Zero . . . . Room 2 (Special Sessions)
- Navigating Knowledge Transfer in the Nuclear Fuel Cycle . . . . Room 3
- Advanced Reactor Deployment: Lightning Talks . . . . Room 5
- Advancing Nuclear Energy Through Modeling, Simulation, AI, and Machine Learning: II . . . . Room 1
- Nuclear Energy: Balancing Communities and the Environment . . . . Room 4

2:45PM **Breaks and Meals**
- Networking Break . . . . TBD

3:15PM **Pacific Basin Nuclear Conference 2024 (PBNC) Technical Sessions**
- Role of Coal Stations in Future Energy Systems . . . . Room 2 (Special Sessions)
- Fuel Cycle Strategies for Enhanced Performance . . . . Room 3
- From Challenges to Opportunities -- Navigating Communities, Environment, and Nonproliferation: Lightning Talks . . . . Room 5
- Advancing Nuclear Energy Through Modeling, Simulation, AI, and Machine Learning: III . . . . Room 1
- Nuclear Safety, Security, and Regulatory Compliance in the Net-Zero World: I . . . . Room 4

6:00PM **Events**
- Gala and Keynote - Billy Mills . . . . TBD

6:00PM **Registration and Exhibit Hall Hours**
- Exhibit open from 7:00AM–4:00PM and 6:00–10:30PM . . . . TBD

Thursday — October 10, 2024

7:00AM **Registration and Exhibit Hall Hours**

- Exhibit Tear Down 7:00 - 10:00 am . . . . . TBD
- Registration/Help Desk open 7:00AM–1:00PM . . . . . TBD

7:00AM **Breaks and Meals**

- Breakfast . . . . . TBD

8:00AM **Pacific Basin Nuclear Conference 2024 (PBNC) Technical Sessions**

- International Advanced Reactor Roundtable - Startup to Demonstration . . . . . Room 2 (Special Sessions)
- Economics of Nuclear Energy in the Net-Zero Era . . . . . Room 1
- Advancing Nuclear Energy: Capabilities, Characterization, and Post-Irradiation Examination: Lightning Talks . . . . . Room 5
- RELAp5-3D Consortium . . . . . Room 3
- Nuclear Safety, Security, and Regulatory Compliance in the Net-Zero World: II . . . . . Room 4

9:45AM **Breaks and Meals**

- Networking Break . . . . . TBD

10:15AM **Pacific Basin Nuclear Conference 2024 (PBNC) Technical Sessions**

- National Laboratory Roles in Nuclear Net Zero . . . . . Room 2 (Special Sessions)
- Emerging Topics in Nuclear . . . . . Room 4
- Modeling and Simulation Advancing Nuclear Energy: Lightning Talks . . . . . Room 1
- Nuclear Fuels and Materials: Lightning Talks . . . . . Room 5

12:00PM **Breaks and Meals**

- Attendee Lunch . . . . . TBD

1:00PM **Events**

- Thursday: Tour of Idaho National Laboratory's Research & Education Campus in Idaho Falls [REGISTRATION HAS PASSED] . . . . . TBD

Experience on Regulating Shutdown Cooling System of RHR during Chinshan Nuclear Power Plant Decommissioning in Taiwan

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doi.org/10.13182/PBNC24-45032

ABSTRACT

Chinshan Nuclear Power Plant (NPP) Unit 1 and Unit 2 entered the decommissioning phase when their operating licenses were expired in December 2018 and July 2019, respectively. Since the reactor core still contained spent fuel, Taiwan Power Company (TPC) has submitted a safety analysis report to Nuclear Safety Commission (NSC) in Taiwan seeking approval to replace the residual heat removal (RHR) shutdown cooling system with the spent fuel pool cooling system and the reactor water cleanup system (RWCU) as alternative cooling measure.

This change is based on experiences from World Association of Nuclear Operators (WANO) and adheres to the technical document TSTF-566 of the United State Nuclear Regulatory Commission (USNRC). To implement this modification, Chinshan NPP has developed a specific procedure for operator to follow. The NSC has completed comprehensive reviews, including technical specifications, testing and monitoring parameters, safety assessments, and contingency plans during decommissioning phase.

To further assess safety, NSC not only reviewed the heat transfer models but also mandated the use of the RELAP-5 program for parallel verification of the temperature data from the upper and lower parts of the reactor core. The NSC has also required TPC to test and measure the actual reactor temperatures for Pre-Defueled Safety Analysis Report (PDSAR) and Pre-Defueled Technical Specifications (PDTS) modification applications.

During the testing, NSC has dispatched resident inspectors for on-site verification to confirm the accuracy of reactor and spent fuel pool temperatures, as well as the availability of alternative cooling system, to ensure the safety of the Chinshan NPP decommissioning.

Keywords: Nuclear Power Plant, Decommissioning, Residual Heat Removal Shutdown Cooling System, TSTF-566, RELAP-5

1. INTRODUCTION

Chinshan Nuclear Power Plant, Taiwan Power Company's (TPC) first nuclear facility, began decommissioning on July 16, 2019, facing space limitations in the spent fuel pools hindering fuel removal. To maintain operations akin to active status, TPC employs the Residual Heat Removal shutdown cooling (RHR S/D) system for decay heat management.

Both units ceased operations prior to decommissioning (Unit 1 in December 2014, Unit 2 in June 2017). During extended shutdowns for testing, operators noted a gradual decrease rather than an increase in spent fuel pool and reactor water temperatures. TPC initiated Special Test Procedure STP-109-01, submitted to the Nuclear Safety Commission (NSC) to explore alternative cooling methods. NSC also invited the experts and scholars of research and academic institutions to review the case, ensuring scrutiny of safety concerns throughout the test period. Their expertise was crucial in evaluating the adequacy of contingency measures for addressing transient events at the nuclear power plant.

NSC conducted a review of nuclear power plants where RHR S/D cooling was placed on standby during extended shutdowns, examining international experiences with alternative cooling methods. TPC contacted the World Association of Nuclear Operators (WANO) regarding similar incidents at Japan's Shimane Nuclear Power Plant. Additionally, experiences from the Cooper and Fermi 2 nuclear power plants in the United States, following NRC Technical Specifications Task Force (TSTF) document TSTF-566, were considered. TPC committed to adhering to the requirements outlined in NRC TSTF-566 during the test period from March 29, 2021 to September 30, 2021. The switch to standby mode for RHR S/D cooling at Chinshan NPP occurred during decommissioning, authorized by NSC upon approval of TPC's Pre-Defueled Technical Specifications (PDTS) modification applications on December 10, 2023.

Table I. Current and Design features of Chinshan NPP in Taiwan.

Plant name	Chinshan Unit 1	Chinshan Unit 2
Reactor Type Vender	BWR – 4 GE	BWR – 4 GE
Containment	Mark – I	Mark – I
Thermal Power (MWt)	1804	1804
Electrical Power (MWe)	636	636
Date of Commercial Operation	12/06/1978	07/16/1979
Date of Cease Operation	12/10/2014	06/02/2017
Date of Decommissioning Period stated	12/05/2018	07/15/2019
Date of Safety Assessment	bounded by unit 2	4/17/2020
Date of Special Test Period STP-109-01	3/29/2021 9/30/2021	3/29/2021 9/30/2021
Date of Modified Technical specifications Approval (TSTF-566)	12/21/2023	12/21/2023

2. DESCRIPTION of PLANT CONDITIONS, TEMPOARY MEASURES, TEST, and MONITORING PARAMETERS

During the extended shutdown, the reactor cavity is kept flooded within the normal range specified for refueling activities. The gates of the Spent Fuel Pool (SFP) are removed, aligning the SFP water level with that of the reactor cavity. Main steam line plugs are installed and the steam lines are drained.

Decay heat from the fuel in both the reactor and the SFP is managed by two systems: the Spent Fuel Pool Cooling and Cleanup System (SFPCCS) and the Spent Fuel Pool Additional Cooling System (SFPACS). Water chemistry in the reactor cavity and SFP is maintained within specified limits through the Reactor Water Cleanup (RWCU) system and the SFPCCS.

NSC assessed the viability of alternative cooling systems like the SFPACS, powered by the fifth air-cooled emergency diesel generator. SFPACS serves as an emergency backup cooling system. If the fuel pool water level drops below the SFPACS pump intake, affecting its cooling function, reactor operators can implement emergency water makeup strategies to ensure continuous cooling. TPC also evaluated the potential impact of siphon reverse flow phenomena on alternative cooling paths. The SFPACS system's pipeline design incorporates two isolation valves, including a check valve that effectively prevents reverse flow of fuel pool water.

In response to NSC's requirements, TPC established test acceptance criteria and contingency measures for abnormal conditions. The acceptance standard, based on the Pre-defueled Safety Analysis Report (PDSAR), mandates that all cooling systems operate below 51.6°C (125°F). If this threshold is exceeded, the test will be suspended, and the additional fuel pool cooling system will be promptly restored, ensuring a sufficient safety margin below the limit of 60°C (140°F).

TPC installed two additional pool temperature-monitoring elements, TE-116-8A/B, positioned 12.8 feet below the surface of the pool (38.1 feet deep), to monitor reactor water temperature during the test period. Additionally, in compliance with improvement requirements post-Fukushima Daiichi accident (USNRC Order EA-12-051 and NEI 12-02), temperature gauges were installed to monitor the spent fuel pool. These, along with the existing RWCU intake temperature gauge below the reactor vessel, effectively monitor reactor and SFP water temperature.

Table II. Design Features for SFPCCS, SFPACS and RHR S/D Cooling in Chinshan NPP.

System **Design Features**	**SFPCCS**	**SFPACS**	**RHR SDC**
Heat Removal(Q_R)	958 kW	4743.4 kW	6515 kW
Flow Rate (m)	500 gpm	1200 gpm	2200 gpm
Design Temperature	< 51.6℃	< 51.6℃	< 51.6℃
NUREG-0800 **SRP 9.1.3 [2]** **Normal Condition**	< 60℃	< 60℃	< 60℃
Abnormal Condition	< 100℃ (SFP only)	< 100℃ (SFP only)	< 66℃ (Rx & SFP)

3. SAFTEY ASSESSMENT

TPC's assessment report initially relied on the decay heat of reactor core fuel from Unit 2 (June 2, 2017) as a conservative benchmark. The decay heat power after 1050 days of Unit 2 shutdown (April 17, 2020) was calculated using the TITRAM/CS/KS-THT-MHD-01 report, leveraging 3-D Computational Fluid Dynamics (CFD) to enhance engineering analysis capabilities, particularly for natural convection dominated thermal hydraulic problems like alternative core cooling during refueling stages. TPC determined that the capacity of the SFPCCS system was adequate to remove the total decay heat from the reactor core and SFP. Despite the absence of forced convection achieved by the RHR S/D cooling operation within the reactor core, TPC assessed that the decay heat of the reactor core fuel could still maintain internal convection within the core. Furthermore, the reactor internals are constructed of corrosion-resistant materials, and water chemistry standards remain consistent with refueling outage protocols, ensuring the integrity of reactor internals and fuels.

NSC scrutinized whether TPC factored in the heat generated by RHR pumps in reactor core heat sink calculations and if it adequately met cooling demands under specified conditions. TPC conducted safety assessments assuming zero heat generation by RHR pumps and heat removal capacity of RHR heat exchangers due to temporary shutdown. Hence, total decay heat removal required consideration for operating one SFPCCS pump and utilizing one heat exchanger, simplifying calculations while maintaining conservatism. TPC outlined calculation basis and formulas to ensure adequacy in removing total decay heat generated by spent fuel during decommissioning.

The review primarily focused on maintaining RHR S/D cooling availability during standby mode. Additionally, concerns centered on the time required for operators to restore RHR S/D cooling or initiate additional fuel pool cooling system operation, and ensuring operators' familiarity with operational procedures. TPC operators estimated RHR S/D cooling restoration within 2 hours and SFPACS activation within 6 hours based on operational experience. To enhance operator capability, TPC committed to conducting surveillance requirements of RHR S/D cooling in the PDTS, ensuring operator familiarity with system operations and periodic increase of forced circulation of reactor water.

TPC utilized heat transfer formulas and the RELAP-5 program to assess safety, evaluating thermal hydraulic models and predicting temperatures above and below the reactor core. Although NSC does not officially approve RELAP-5 program use, TPC clarified that its analysis results serve as references for evaluation, with actual test results forming the basis for future analysis and PDTS modification applications.

Given the deviation from normal shutdown operations where the RHR system maintains constant flow for forced convection, the absence of water flow due to RHR S/D cooling shutdown may lead to stratification and stagnant water conditions in the reactor core. TPC's analysis of RHR S/D cooling standby mode suggests that while reactor core water flow may be affected, decay heat will still induce thermal convection, preventing stagnant water flow. After RHR S/D cooling standby, TPC noted minimal stratification effects, with a temperature difference above the reactor core of only 1°C to 4°C according to analysis results. Additionally, to verify actual temperatures, temperature gauges were installed to monitor reactor and SFP water temperature, with operators recording relevant trends hourly during the test period to validate RELAP-5 program simulation results.

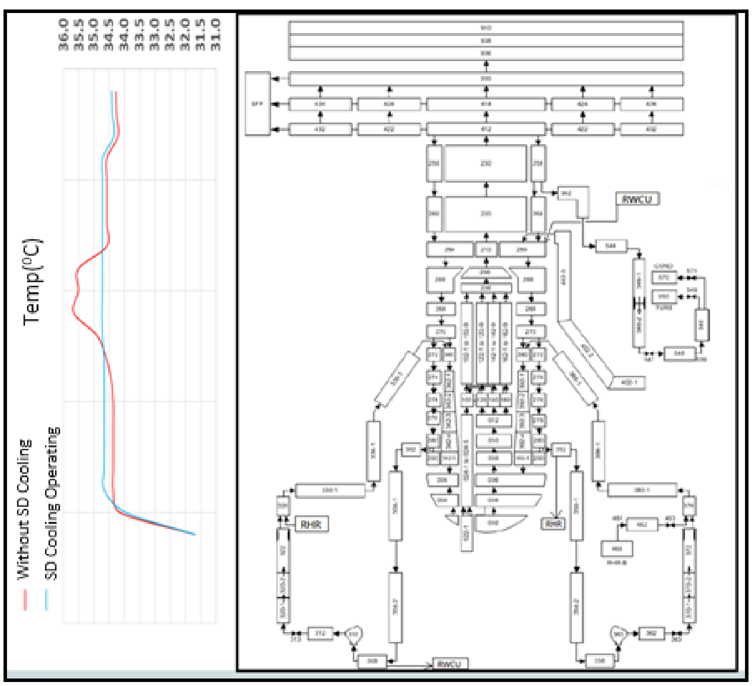

Figure 1. Simulated the Reactor Cavity of Chinshan NPP in RELAP-5 Program.

4. CONTINGENCY RESPONSE

During the testing period, TPC provided analyses and explanations for potential abnormal conditions, such as failures of the SFPCCS, loss of offsite power (LOOP), and loss of reactor cavity or fuel pool water levels.

Since the application only places the RHR system on standby without cessation of any safety systems, regular testing of the RHR system continues to verify its availability.

NSC reviewed whether reactor water temperature exceeding the test acceptance criteria during the testing period would necessitate proposing contingency measures. TPC clarified that the SFPCCS system's design capability ensures greater heat removal capacity than the total decay heat of the reactor, maintaining reactor and SFP water temperatures below or equal to 51.6°C. If temperatures approach the safety limit, operators can adjust the operating configuration, such as using additional SFPCCS pumps and heat exchangers. Additionally, Chinshan NPP's higher capacity SFPACS can be initiated within 6 hours. If both SFPCCS and SFPACS systems are unavailable, standby RHR S/D cooling will be initiated within 2 hours for core cooling, maintaining a safe reactor water temperature rise rate of 0.438°C/hr. This contingency time ensures safety through diversity, redundancy, and defense in depth.

Additionally, the adequacy of alternative cooling systems (RWCU, SFPCCS) in the event of offsite power loss was considered, particularly regarding potential failure due to insufficient essential bus power supply or seismic design capability to maintain their original heat removal functions. TPC clarified that in the event of offsite power loss, Emergency Diesel Generators (EDG) would automatically start, and operators could gradually initiate alternative cooling systems after confirming essential bus power availability. Moreover, the current alternative cooling systems undergo substantial seismic margin assessment. Should these systems become unavailable, RHR S/D cooling, classified as seismic category I, would be immediately restored approximately 1 to 2 hours.

In terms of contingency plans, NRC requires TPC to address incidents such as Station Blackout (SBO) events and assess if existing procedures can manage prolonged SBO incidents. TPC explained that Chinshan NPP, in alignment with strategies post-Fukushima, has implemented three external water makeup and spray strategies: portable SFP makeup, SFP spray, and Backup Containment Spray System (BCSS) water injection using fire engines, ensuring fuel safety during SBO events.

TPC considered the incident at River Bend Unit 1, attributing it to main steam line plug failure resulting in water loss from the upper pool and reactor cavity. However, at Chinshan Nuclear Power Plant, main steam line plugs are already in place, with the System Evaluation and Reclassification Team (SERT) conducted during decommissioning. The inboard/outboard closure of main steam isolation valves (MSIV) in the primary containment provides two additional barriers. Even if main steam line plugs were to fail, there would be no water loss from the reactor cavity. TPC has positioned one RHR train in low pressure coolant injection (LPCI) mode and the other in SDC mode to address potential water loss from the reactor cavity and SFP.

In TPC's safety analysis report, conservative assumptions from current licensing basis (CLB) such as PDSAR were utilized. This assumed a leakage at the bottom of the reactor cavity without considering the leakage rate and required time. The water level was assumed to drop directly to the bottom of the SFP gate. Based on this water volume, the time required to reach boiling temperature was calculated. Although analysis based on the actual leakage rate indicated a boiling time exceeding 19 hours, the safety assessment still conservatively utilizes a 19-hour basis as outlined in the PDSAR.

Table III. Calculations of Decay Heat during Loss of Power and Heat Sink in Chinshan NPP.

Chinshan Unit 2 **(Shutdown 1050 days)**	**Reactor Cavity**	**SFP**
Standard	ANSI 5.1 − 2014[4]	ANSI 5.1 − 2014
Decay Heat(Q)	257.1kW	652.1kW
Volume (V)	878.58 m^3	938.32 m^3
Density (d)	983.38 kg/m^3	same as reactor
Cp	4178 J/kg°C	same as reactor

Formula	$\Delta T = Q / (V \times d \times Cp)$	same as reactor
Raise Temp	$0.438\,°\frac{C}{hr}$	same as reactor

5. TEST CONTENT and RESULTS

During the testing period for Chinshan Nuclear Power Plant Unit 1 and Unit 2, spanning from March 29, 2021 to September 30, 2021, TPC conducted the Special Test Procedure document STP-109-01 "Operation Record of Reactor Water Temperature and Spent Fuel Pool Water Temperature Changes during Continuous Operation of Residual Heat Removal Cooling Function. " TPC verified three operating configurations of the SFPCCS as follows, while adhering to decommissioning technical specifications:

(1) One SFPCCS cooling pump + two sets of SFPCCS heat exchangers

(2) One SFPCCS cooling pump + one set of SFPCCS heat exchangers

(3) Two SFPCCS cooling pumps + two sets of SFPCCS heat exchangers

The testing period was divided into three phases:

(1) Phase One (March 29 to May 31): Focused on operator familiarization with the operation of different configurations and understanding the effects of regular tests.

(2) Phase Two (June 1 to July 15): Transitioned operational configurations based on changes in sea water temperature, with lower cooling capacity configurations used as sea water temperature increased.

(3) Phase Three (July 15 to September 30): Mainly operated with one SFPCCS cooling pump and one set of heat exchangers.

The average temperature of the reactor core water is measured by TR-G33-R607-1 (RWCU inlet), TR-B31-R650-1 (Recirc. Loop-A), and TR-B31-R650-2 (Recirc. Loop-B) as specified in the Special Test Procedure document STP-109-1. During the RWCU maintenance or related testing pause, the temperature gauge (TR-B21-R614-CH.2/PPCRS SRV026) on the Wide Range Neutron Monitor (WRNM) spare dry tube serves as an alternative for monitoring reactor core temperature. Reactor cavity temperature is determined by the average of temperature sensors CT01/CT01A and CT02/CT02A. Post-review the detectors and recorders installed in the reactor cavity will be removed to avoid interfering with spent fuel remove on the refueling floor of the reactor building. The temperature of the spent fuel pool is the average of LR/TR-116-8A/B as shown in the figure below.

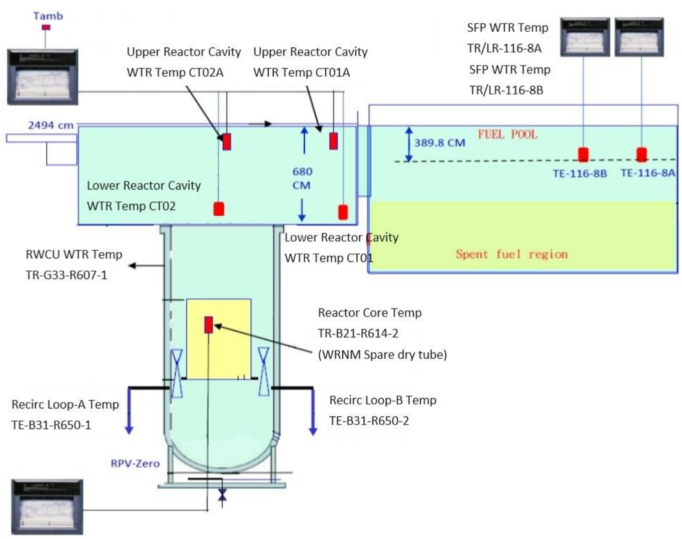

Figure 2. The Instruments of Temperature in the Reactor Core, Reactor Cavity and Spent Fuel Pool in the Special Test Procedure.

In addition to familiarizing operators with the three operating configurations, the planned tests assessed the impact of sea water temperature on reactor core and SFP water temperatures under different SFPCCS setups. The highest sea water temperature recorded during testing was approximately 29.6°C on September 5. Even during this period, when only one SFPCCS cooling pump + one set of heat exchangers was used, reactor water temperature remained below 40°C, meeting the special procedure temperature limit of 51.6°C.

The highest sea water temperature observed differed from the previously recorded 33°C. TPC must ensure that simultaneous operation of multiple equipment does not exceed estimated temperature ranges. Operational experience suggests that under extreme conditions, including operation of radwaste boilers and emergency diesel generators, the CSCW heat exchange may raise water temperature by approximately 7°C. With a 3°C sea water temperature increase, operating one SFPCU pump + one set of heat exchangers could raise reactor and SFP water temperature by approximately 10°C. Despite the shorter shutdown period and higher decay heat from Unit 2 spent fuel, with a water temperature of around 48.1°C, there remains a safety margin of about 3.5°C from the 51.6°C limit.

TPC performed regression analysis on water temperature data from Units 1 and 2, along with sea water temperature data, from July 15 to September 30. They found a positive linear correlation between furnace water temperature and sea water temperature. For Unit 1 and Unit 2, a 1°C rise in sea water temperature corresponded to an average increase of approximately 0.39°C and 0.4°C in water temperature, respectively. Therefore, assuming sea water temperature variations mirror water temperature variations is considered a conservative approach when assessing water temperature at sea water temperatures reaching 35°C.

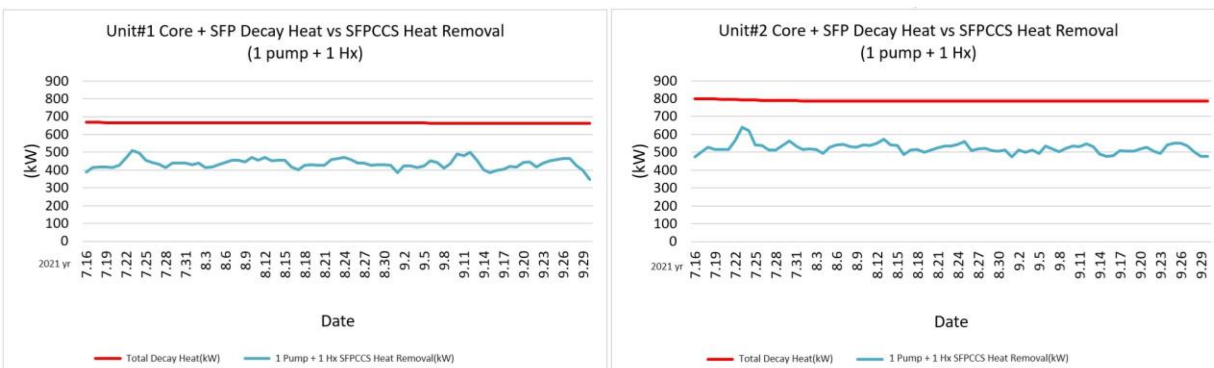

Figure 3. The Decay Heat from Reactor and Spent Fuel Pool vs the Capacity of Heat Remove from SFPCCS (1Pump + 1Hx) in Unit 1 and Unit 2.

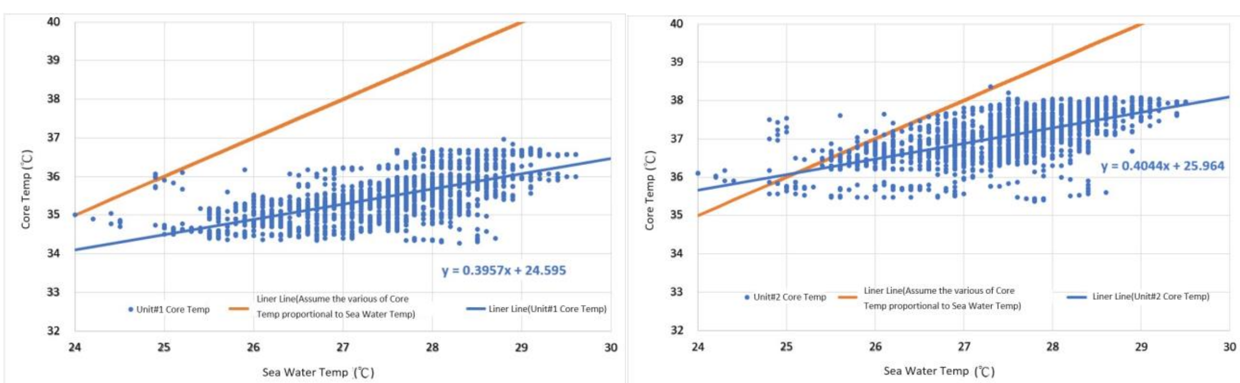

Figure 4. **The Trends of Temperature between Sea Water and Reactor Water in Unit 1 and Unit 2.**

6. COMPARISON of TEST RESULTS and SAFETY ANALYSIS RESULTS

TPC's safety analysis report identifies decay heat from the reactor core and SFP, along with heat generated by continuous SFPCCS and RHR system pump operation, as primary heat sources. Heat sinks include the cooling functions of SFPCCS and RHR system heat exchangers, heat dissipation from surrounding surfaces, and natural convection heat dissipation at openings above the reactor cavity and SFP. According to the analysis, the SFPCCS system can entirely remove residual heat from spent fuel.

Referring to relevant analysis data from the PDSAR, we can calculate the heat transfer rate of a single-train heat exchanger in the SFPCCS system. Heat exchange efficiency is 0.44 which is determined by the ratio of the minimum flow side inlet-outlet temperature difference to the maximum temperature difference at the heat exchanger's inlet and outlet.

TPC's test report indicates an estimated average decay heat of approximately 787 kW for reactor core and SFP fuel in Unit 2. Originally, heat removal was calculated based on water temperature at the heat exchanger inlet, without factoring in heat loss from piping and ambient temperature at the water surface of the reactor cavity overflow. To address this, using the water temperature at the reactor cavity overflow to skimmer surge tank for calculation can eliminate these influencing factors, resulting in a more accurate heat removal calculation of about 500-600 kW. As a result, the revised content should state that the heat removed by the heat exchanger exceeds the total decay heat by about 187-287 kW. Heat dissipation from the reactor wall and pool water surface amounts to about 90 kW. Considering a temperature sensor error of +/- 0.5°C, this inaccuracy may result in a deviation of 66 kW in heat removal. The additional 31-131 kW (3.9-16.6%) should come from conservative overestimation of decay heat and burnup.

TPC provided supplementary calculations for Unit 1, showing an estimated average decay heat of about 663 kW for the reactor core and spent fuel pool fuel. The heat removal is approximately 400-500 kW, with the heat removed by the heat exchanger exceeding the total decay heat by about 163-263 kW. Heat dissipation from the reactor wall and pool water surface amounts to about 90 kW, with the inaccuracy of temperature instrument about 66 kW. The additional 7-107 kW (1.1-16.1%) should come from conservative overestimation of decay heat and burnup.

Table IV. **Comparison of Calculations and Test Period of Decay Heat from Reactor Cavity and SFP in Chinshan NPP.**

Chinshan	Unit 1 Test Period (Shutdown 2500days)	Unit 2 Test Period (Shutdown 1500days)
Standard	ANSI 5.1 − 2014	ANSI 5.1 − 2014
Formula	$QR = m \times Cp \times \eta \times \Delta T$	same as unit 1
SPFCCS flow rate (m)	31.55 kg/sec (500 gpm)	same as unit 1
Cp	4.18 kJ /kg°C	same as unit 1
η	0.44	same as unit 1
$\Delta T = T_{SFP} - T_{coolant}$	51.6°C − 37.6°C	51.6°C − 37.6°C
Decay Heat from Reactor and SFP (Q_T)	663 kW	787 kW
Heat Remove from SFPCCS (Q_R)	400~500 kW	500~600 kW
Heat Loss from Reactor And SFP (Q_L)	90 kW	same as unit 1

Instrument Inaccuracy (Q_I)	66 kW	same as unit 1
Uncertainty (Q_U)	7~107 kW	31~131 kW
Energy Conservation	QT = QR + QL + QI + QU	

Based on the simulation program analysis, the temperature difference between the core temperature (Tcore) and the cavity (TC01A/TC02A) is approximately 0.8-1.1°C. The simulated flow rate of cooling water in the core is estimated to be about 0.42 cm/sec. Comparison of the analysis results with the plant's test data shows consistency between the two sets of data, indicating no stagnation in the water flow in the core.

During the implementation of the STP-109-1 test from March 29 to September 30, 2021, prior to the cessation of operation of the RHR S/D cooling pump on March 29, the reactor water temperature for Unit 1 decreased from 31.9°C to 26.9°C over 2 days. Similarly, for Unit 2, the reactor water temperature decreased from 32.8°C to 28.4°C over 2 days. These observations suggest that the heat energy generated by the rotation of the pump blades during the operation of the current RHR S/D cooling pump is carried to the core, resulting in a heating phenomenon in the reactor water temperature.

7. VERIFICATION and INSPECTION of SPECIFICAL TEST PROSEDURES

During the standby testing of the RHR system at Chinshan NPP, NSC mandated TPC to meticulously record various parameters, including reactor water temperature, water chemistry, and Heating, Ventilation and Air Conditioning (HVAC) configuration on the refueling floor of the reactor building. NSC also devised inspection plans for on-site verification by inspectors, both before and after the test, as well as during daily presence at the plant, to ensure the accuracy of test records and unit conditions.

Throughout the testing period, NSC inspectors verified whether the plant adhered to commitments by accurately recording parameters like reactor pool water temperature and water quality. They also monitored critical equipment start-up, shutdown timing, and execution of periodic tests. Simultaneously, NSC inspectors confirmed TPC's compliance with quality assurance standards per 10 CFR 50 Appendix B. The comprehensive inspection results revealed no deviations from regulations or commitments during this test period, indicating the successful implementation of the RHR system standby testing at Chinshan NPP.

8. COMPARISON of TECHNICAL SPECIFICATION MODIFICATIONS with TSTF-566

The United States Nuclear Regulatory Commission (USNRC) approved TSTF-566 “Revise Actions for Inoperable RHR Shutdown Cooling Subsystem” on February 21, 2019.The revisions made by TPC to the technical specifications LCO 3.9.7 and related BASES for Chinshan Nuclear Power Plant, following the spirit of TSTF-566, are as follows:

(1) LCO 3.9.7 is divided into NOTE 1: RHR SDC can be stopped for 2 hours every 8 hours when the spent fuel pool gate is closed; and NOTE 2: When the cooling water temperature is less than 51.6°C (125°F) and the spent fuel pool gate is open, one RHR SDC alternative cooling system is in operation.

(2) Specify that the original SR 3.9.7.1 (verify RHR SDC operation every 12 hours) does not apply to NOTE 2 condition.

(3) Add SR 3.9.7.2 to confirm the reactor water temperature is less than 51.6°C (125°F) every 12 hours.

(4) Add SR 3.9.7.3 to confirm an alternative SDC method is in operation every 12 hours.

(5) Add SR 3.9.7.4 to verify RHR SDC operation for two hours every 92 days, these three new surveillance tests apply to NOTE 2 condition.

9. CONCLUSIONS

The application of RHR S/D cooling during the decommissioning of Chinshan NPP was reviewed by the NSC, covering interim measures, testing and monitoring parameters, safety assessment, and response to abnormal conditions. TPC revised and reorganized the report content according to review comments. Upon NSC review, the results were acceptable, and the safety assessment report was approved.

To inspect TPC implements interim measures and review commitments, and to verify the conformity of the test results and safety analysis reports of the "STP-109-01 Shutdown Cooling System Standby Test Report" during the formal testing period, NSC implemented an inspection plan to verify the conditions of reactor and SFP water temperature and related cooling systems operability on-site. Additionally, the technical specification modification proposal in this case referenced the revision of the TSTF-566, incorporating modifications to the simulator's RHR system standby configuration into the annual operator-retraining course, including simulator course, and on-site walk down.

To verify the availability of the RHR system after standby, NSC required that the maintenance and surveillance cycle (MSC) of the RHR system during decommissioning be consistent with the refueling outage in the operating period to maintain its reliability. Furthermore, NSC established inspection frequencies for the reactor inspection program, such as equipment configuration, surveillance tests, heat sink efficiency, and maintenance rules related to spent fuel pool cooling systems based on the USNRC IMC 2561[5] decommissioning inspection items to ensure fuel safety.

ACKNOWLEDGMENTS

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The Public Protective Action Guides for Nuclear Emergency in Taiwan

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ABSTRACT

Lessons learned from the 2011 nuclear accident at Tokyo Electric Power Company's Fukushima Daiichi nuclear power plant in Japan have led international community to revise implementation recommendations and guidelines for the public protective actions in a nuclear emergency. Taiwan used to adopt dose evaluation system combined with intervention levels to determine the timing of implementing the public protective actions in a nuclear emergency. It was widely used internationally however had been demonstrated to be impractical in the Fukushima accident.

Referring to lessons from Fukushima accident and related international guidance, Taiwan government had substantially revised the nuclear emergency classification, and kicked-off criteria of nuclear emergency response mechanism. Key amendment includes the application of: (1) emergency action levels (EALs) for precautionary protective actions, and (2) operational intervention levels (OILs) for urgent protective actions. This mechanism is constantly reviewed and improved through conducting nuclear emergency exercise and referring international documents. Building a emergency response scheme ensuring nuclear safety is the only way to achieve a sustainable nuclear future.

Keywords: public protective actions, dose evaluation system, EALs, OILs

1. INTRODUCTION

An emergency at a nuclear power plant that involves damage of nuclear fuel in reactor core or in a spent fuel pool might cause radioactive material released to atmosphere and possibly lead to severe health effects including deterministic effects of acute radiation exposure and stochastic risks of chronic radiation exposure. These effects can be prevented or mitigated by prompt implementation of public protective actions. In Taiwan, these actions include shelter in house, evacuation, relocation, decontamination, iodine tablet administration, and food and drinking water restriction.

The timing of implementing public protective actions should be determined through prudent assessment in order to reduce the risk of radiation exposure. Protective actions will be undertaken only when well-evaluated to be safe and would not endanger the lives of those being evacuated or relocated, especially those individuals should be treated in intensive-care units (e.g. patients in intensive care in hospitals or people in nursing homes).

In Taiwan, the Central Disaster Response Center (CDRC) is the major role making decisions on when and what protective action to be taken in a nuclear emergency based on summative assessments among the dose evaluation system, EALs, and OILs.

2. MECHANISMS

Current nuclear emergency response mechanisms on initiating off-site public protective actions in Taiwan are dose evaluation system and concepts known as EALs and OILs, which are introduced as below.

2.1. Regulation and Framework of Public Protective Actions

According to Taiwan's Nuclear Emergency Response Act[1], the central competent authority, i.e. Nuclear Safety Commission(NSC), shall consult each designated agency to lay down the Emergency Response Basic Plan[2] and the Nuclear Emergency Public Protective Action Guides[3], then submitted to the Executive Yuan for approval. The regional competent authority, i.e. local government, shall then lay down the regional public protection plan within the emergency preparedness zone (EPZ) according to the Emergency Response Basic Plan and the Nuclear Emergency Public Protective Action Guides. Once a nuclear emergency happened, the regional competent authority should carry out public protective actions while corresponding orders given by the CDRC, which is the highest tier of decision-making on the public protective actions. The CDRC takes major responsibility of decision-making on nuclear public protective actions in accordance with relative information, which includes accident conditions, radiation dose estimated and field monitoring data.

When it comes to a nuclear accident, the nuclear reactor facility licensee shall notify the competent authorities of various tiers within 15 minutes, and in writing within one hour according to Taiwan's Guidelines for Nuclear Accident Classification, Notification and Response[4]. After completing the preceding notifications, and before the termination of the accident, licensee shall, submit every hour a written report including the following items to the competent authorities of various tiers: (1)current status of the plant; (2)causes of the accident; (3)trend of the accident; (4)status of radioactive material release; (5)relevant response measures taken.

Upon receiving the notification, the central competent authority, which is NSC, shall follow the "Emergency Response Basic Plan" to take the response measures promptly and report to the Executive Yuan at appropriate time based on the progress of the nuclear accident and to set up the National Nuclear Emergency Response Center to proceed with response measures.

Regional Nuclear Emergency Response Center is in charge of carrying out the response measures according to their nuclear emergency public protection plan and referring to the guide from CDRC. Nuclear Emergency Support Center from the Ministry of National Defense would assist in disaster relief. The Radiation Monitoring and Dose Assessment Center is composed of NSC, Central Weather Bureau, Ministry of National Defense, Coast Guard Administration of Ocean Affairs Council, and the licensee. The Radiation Monitoring and Dose Assessment Center is responsible for environmental radiation detection, the affected areas estimated and prediction of the radiation exposure scope of the accident. Accordingly, the Radiation Monitoring and Dose Assessment Center performs public dose evaluation and makes appropriate recommendations on public protective actions to the CDRC. It also takes samples of soil, grass and agricultural produces from the potentially contaminated area for radiological analysis. The Radiation Monitoring and Dose Assessment Center also would ask military to carry out aerial radiation survey while situation worsening and radioactive materials released. Also, the coast guard could be asked to send patrol ships to detect radiation, and to collect sea water and fish samples for preliminary analysis to understand the distribution and contamination status of radioactive material. Moreover, water samples from the neighboring water treatment works is conducted to ensure drinking water free from contaminated of radioactive material.

2.2. Mechanism

The failure of the CDRC to implement appropriate the public protective actions in affected areas timely could result in the occurrence of avoidable severe health effects. Taiwan used to adopt the mechanism known as dose evaluation system combined with concepts of intervention level to determine when to implement nuclear emergency public protective actions, which was widely used internationally and had been demonstrated to be impractical in the Fukushima accident. Therefore, referring to lessons learned and related international guidance[5][6][7], Taiwan had adopted EALs and OILs systems and had issued corresponding guidance in the following years after the accident at Tokyo Electric Power Company's Fukushima Daiichi nuclear power plant in Japan in 2011. That is, the mechanism including the dose evaluation system, the concepts of EALs and OILs which help the CDRC on determining the implementation time of public protective actions. They are presented as follows.

2.2.1. Dose evaluation system

"Nuclear Emergency Public Protective Action Guides" was issued in 2005, in which lists the procedures and criteria known as intervention level, averted dose and projected dose of each protective action, as shown in Table I. When the calculated results of the evaluated dose appear to exceed the intervention level, undertaken of corresponding measures will be suggested to the CDRC.

Table I. "Nuclear Emergency Public Protective Action Guides" issued in 2005

Measure	Intervention Level
Shelter	Averted Dose: ≥10 mSv in 2 days
Evacuation	Averted Dose:50-100 mSv in 7 days
Iodine Tablet Administration	Averted Dose: ≥100 mSv of HT(thyroid)
Temporary Relocation	Projected Dose: ≥30 mSv in 30 days
Food and Water Restrictions	Defined by different Radionuclide
Permanent Relocation	(1) Projected Dose:≥ 1 Sv in lifetime (2) Temporary Relocation over 1 year

Dose evaluation system is the computer program used to assess the intervention levels and capable of demonstrating simulation of released radiological material with atmospheric diffusion and calculation of averted dose rate around the plant (Figure 1). For accurate calculation, information of radionuclide source term in the fuel in the nuclear power plant, meteorological data, and release path of radiological material are all needed.

After the Fukushima accident in 2011, this type of decision making process based on the computer-prognosis system was verified to be impractical due to unpredictable precipitation related to constantly changed wind direction, and source term data which is difficult to obtain while chaotic accident situation, these factors all lead to the increase of inaccuracy of the calculated results.

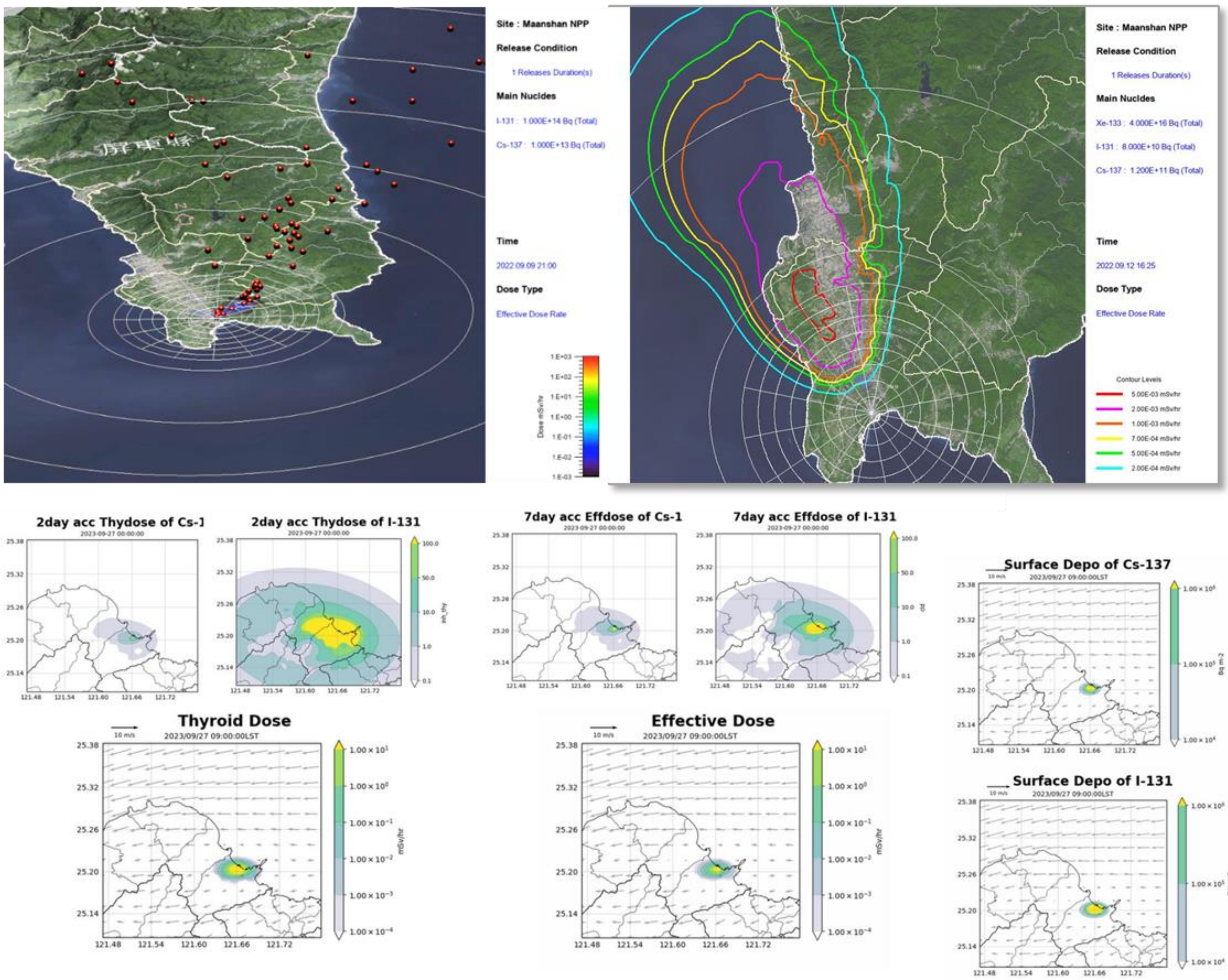

Figure 1. Analysis Data of the Dose Evaluation System

2.2.2. Emergency Action Levels (EALs) System

Released radioactive material from the plume formed by damaged fuel can possibly result in adverse health effects within hours in the most severe condition if protective actions are not promptly taken. Since the timing of a radiation release is generally hours delayed since the damage of nuclear fuel or malfunction of critical safety features of nuclear power plant (NPP), actions to protect the public could be initiated earlier according to predetermined operational criteria of safety parameters from accident plant. Emergency action levels (EALs) system is a predetermined and observable criteria used for decisions on the implementation of protective actions corresponding to the nuclear emergency category.

"Guidelines for Nuclear Accident Classification, Notification and Response"[4] was revised in 2016 in which provided the criteria on classification of nuclear emergency. According to the guideline, upon detection of the incident or its symptoms, the nuclear power plant shift supervisor should declare the emergency classification referring from NEI 99-01[8] and reported to the competent authority, which is NSC, for approval.

Nuclear emergency was classified into three categories in Taiwan based on increasing levels of hazard and tied to the response needed for the protection of the publics, which are Alert, Site Area Emergency and General Emergency.

- Alert: A worsening of the safety functions of a nuclear reactor facility but not yet requiring public protective action.
- Site Area Emergency: A major loss, or possible major loss, of safety functions of a nuclear reactor facility with possible public protective action taken..
- General Emergency: A serious, or possibly serious, deterioration of the reactor core of a nuclear facility with the possible loss of integrity of the containment structure requiring public protective actions.

"Guidelines for Nuclear Accident Classification, Notification and Response" provides the criteria of each category with the description of predetermined conditions and instrument readings in the nuclear power plant, mainly according to radiation levels, safety systems and other potential hazard condition. The classifications of nuclear emergency are the EALs, which are based on the information that is observable in the control room by operators and is indicative of the possibility of damage to the fuel in reactor core or in spent fuel pool. After approval, the declaration of each classification would trigger coordinated response measures by all response organizations. According to the "Reference Guidelines for Decision Making on Public Protective Actions in a Nuclear Accident"[9] issued in 2018, the predetermined actions each organization has to take upon declaration of the emergency are as illustrated in Table II.

Table II. EALs and corresponding recommended public protective actions

<table>
<tr><th rowspan="2"></th><th colspan="3">Classification of Nuclear Emergency</th></tr>
<tr><th>Alert</th><th>Site Area Emergency</th><th>General Emergency</th></tr>
<tr><td rowspan="3">Public Protective Action</td><td colspan="3">Close public recreation areas</td></tr>
<tr><td></td><td colspan="2">1. Issue nuclear emergency siren
2. Precaution evacuate vulnerable populations within EPZ
3. Instruct generic public within EPZ to shelter in house</td></tr>
<tr><td></td><td></td><td>Evacuate generic public within 3 km</td></tr>
</table>

Upon declaration of "Alert", the public recreation area inside EPZ will be closed and all the tourists will be asked to leave immediately. Traffic control should be implemented to prevent individuals or vehicles from entering EPZ. Upon declaration of a "Site Area Emergency", the nuclear emergency siren would be issued, meanwhile precaution evacuation of the vulnerable populations and shelter instruction of generic public within EPZ will be implementing.

The siren and notification will be delivered to the publics via a pre-established emergency alert system includes alert and notification systems by licensee, radio broadcast, village radio stations, vehicle broadcast, social media, internet web sites, text message, telephone, TV, CBS, etc...... Once the alert being issued, the affected villages and the police will urge the public to stay indoors, ensure the doors and windows are closed, turn on TV or radio for information updated and waiting for further instructions.

Another action to be undertaken includes precaution evacuation of vulnerable populations within the EPZ. After Fukushima accident, in order to prevent mass casualty due to large scale evacuation, staged evacuation had been adopted. In the stage of "Site Area Emergency", population need special help includes residents in nursing homes and hospitals, and transportation dependent residents, will be instructed to evacuate. In addition, generic public within 8 km will be instructed to shelter in house.

Upon declaration of "General Emergency", it is crucial to instruct all the residents living within 3 km around the nuclear power plant to evacuate immediately as soon as it is possible to do so safely.

Each category of nuclear emergency warrants off-site response organizations to alert the public or to start implementation of the predetermined urgent protective actions as shown in Table III. Off-site emergency response guidelines need to be identified in advance during the preparedness phase of emergency management. This is to ensure that effective protective actions and other response actions can be promptly and appropriately implemented to protect the public that are consistent with the hazard.

Table III. Emergency Response Guidelines for Response Organizations

	Alert	Site Area Emergency	General Emergency
Licensees	1. Activate onsite emergency response organization. 2. Phone notification to competent authority within 15 minutes; submit written report every hour. 3. Rush repair. 4. Onsite radiation detection. 5. Accident assessment. 6. Check availability of alert and notification system.	1. Phone notification to competent authority within 15 minutes; submit written report every hour. 2. Rush repair. 3. Onsite radiation detection. 4. Accident assessment and dose evaluation.	1. Phone notification to competent authority within 15 minutes; submit written report every hour. 2. Rush repair. 3. Onsite radiation detection. 4. Accident assessment and dose evaluation
National Nuclear Emergency Response Center	1. Declaration of nuclear accident classification and Emergency Activation Level-2. 2. Command to close public recreation areas. 3. Press release.	1. Declaration of nuclear accident classification and Emergency Activation Level-1. 2. Command to: (1) Issue nuclear emergency sirens. (2) Inform public to shelter in house. (3) Precautionary evacuate special needs group within EPZ. 3. Press release.	1. Declaration of nuclear accident classification. 2. Command to : (1) Evacuate public within 3 km. (2) Inform Public in the region of 3-8 km to shelter in house. 3. Press release.
Regional Nuclear Emergency Response Center	1. Emergency Activation Level-2. 2. Close public recreation areas and inform tourist to evacuate. 3. Contamination screening stations setup preparedness. 4. Traffic control. 5. Press release.	1. Emergency Activation Level-1. 2. Issue nuclear emergency sirens. 3. Inform public to shelter in house. 4. Precautionary evacuate special needs group within EPZ. 5. Contamination screening stations activated. 6. Traffic control. 7. Press release. 8. Reception center preparedness	1. Evacuate public within 3 km. 2. Inform Public in the region of 3-8 km to downwind side shelter in house. 3. Reception Center activated. 4. Iodine tablet arrangement and distribution. 5. Traffic control. 6. Press release.

Nuclear Emergency Radiation Monitoring and dose assessment center	1. Emergency Activation Level-2. 2. Meteorological data collection. 3. Check availability of alert and notification system.	1. Emergency Activation Level-1. 2. Issue nuclear emergency sirens. 3. Land radiation detection within EPZ. 4. Joint operation at contamination screening stations. (personnel and vehicle radiation detection) 5. Dose evaluation and PPAs suggestion. 6. Mobile radiation detection deployment.	1. Dose evaluation and PPAs suggestion 2. Radiation detection. (land, sea and air) 3. Environmental sampling and laboratory analysis.
Nuclear Emergency Support Center	1. Emergency Activation Level-2.	1. Emergency Activation Level-1. 2. Joint operation at contamination screening stations. (personnel and vehicle decontamination) 3. Traffic control and area control. 4. 8-16 km land radiation detection.	1. Joint operation at contamination screening stations and reception center. 2. Support air radiation detection. 3. Traffic control and area control.

2.2.3. Operational Intervention Levels (OILs) System

Following a release of radioactive material from the reactor core or spent fuel pool from deterioration of the accident, those areas not evacuated should be promptly monitored to identify contaminated area and hotspots in order to implement urgent protective actions and additional response actions based on environmental radiation level.

Operational intervention levels (OILs) are the predetermined values transformed from generic criteria of particular protective actions, which could immediately and directly trigger corresponding actions in nuclear emergency. Predetermined OILs in Taiwan are illustrated in table IV according to “Reference Guidelines for Decision Making on Public Protective Actions in a Nuclear Accident”. The main idea of this reference guideline is to identify areas with hotspots in order to help the CDRC make comprehensive decisions on public protective actions after a radioactive release.

As showed in table IV, four OILs are used in Taiwan. Upon the environmental radiation measurements from field monitoring instruments or laboratory analysis exceeding these OILs, particular response action will be conducted. Among these predetermined operational criteria,OIL1, OIL2 and OIL3 are provided for ground deposition dose rates (μSv/h at 1 m above ground level) used to determine where warrant evacuation, relocation or restrictions on food and drinking water that may have been contaminated. As soon as OIL1 is exceeding, public in the affected areas should be instructed to evacuate immediately. Once the monitoring results exceed OIL2, residents in the affected area should be informed to relocate in accordance with complete program in weeks to months. OIL 3 is to decide if off-site decision maker should instruct to restrict consumption of food and drinking water which could represent a risk with contamination until further assessments are performed. OIL4 is used to examine if radioactive material deposition on the skin of individuals exceeding limitations and decontamination procedures needed.

Meanwhile, the dose evaluation system is still proceeding and updating the predicted dose as assistance for CDRC to make more comprehensive decisions on protective actions, as a result, the table V also lists part of the interventional levels from “Regulations for Public Protective Actions in Nuclear Accident” to make it more easy to use for off-site decision makers.

Table IV. OILs and intervention level of public protective actions

		Operational Intervention Levels		**Intervention Level**
Timing		After radionuclide released		Before and After radionuclide released
Measures	Shelter			Averted Dose: ≥10 mSv in 2 days
	Iodine Tablet Administration			Averted Dose: ≥100 mSv of $H_{T(thyroid)}$
	Evacuation	OIL1	Dose rate at 1m above ground level：> 500μSv/h	Averted Dose:50-100 mSv in 7 days
	Temporary Relocation	OIL2	Dose rate at 1m above ground level：> 20 μSv/h	
	Food and water Restrictions	OIL3	Dose rate at 1m above ground level：> 0.5μSv/h	
	Decontamination of Individuals	OIL4	Dose rate at 10cm from skin：>1μSv/h	

3. APPILICATION

After the foregoing emergency response scheme was put into effect, relevant response units were in charge of formulating procedures, preparing essential equipment and carrying out personnel training.

The foregoing emergency response scheme was put into practice in Taiwan’s annual full-scale nuclear emergency exercise to validate the feasibility and availability. It’s also an excellent opportunity for related competent authorities and response personnel to get familiar with the mechanism.

Take 2022 nuclear emergency exercise to illustrate, which was launched at Maanshan NPP in southern Taiwan to practice and test the nuclear emergency response plans and procedures. The scenario simulation was complex disaster which includes nuclear accident, earthquake, storm surges, and pandemic, triggers a loss of both onsite and offsite AC electric power supply. The simulated accident turned out deteriorating into General Emergency and led to release of radioactive material.

At the beginning of the exercise, the EALs system has been applied upon a situation of Alert was achieved toward declaration of a nuclear emergency, which prompted all response units to implement corresponding PPAs according to Table III. The dose evaluation and environmental radiation monitoring were carrying out immediately after relevant response units have settled in. Successively the OIL system has been activated when radioactive material released. Environmental radiation monitoring through field detection of land, sea and airborne, as well as environmental sampling and laboratory analysis, all collected data would be integrated into a unified platform.(Figure 2) Once any data or reading exceeding the limitations shown in Table IV, corresponding response actions will be executed in accordance with command from CDRC. Meanwhile, the dose evaluation system keeps on proceeding and updating the predicted dose as assistance for CDRC to make more comprehensive decisions on protective actions. (Figure 3)

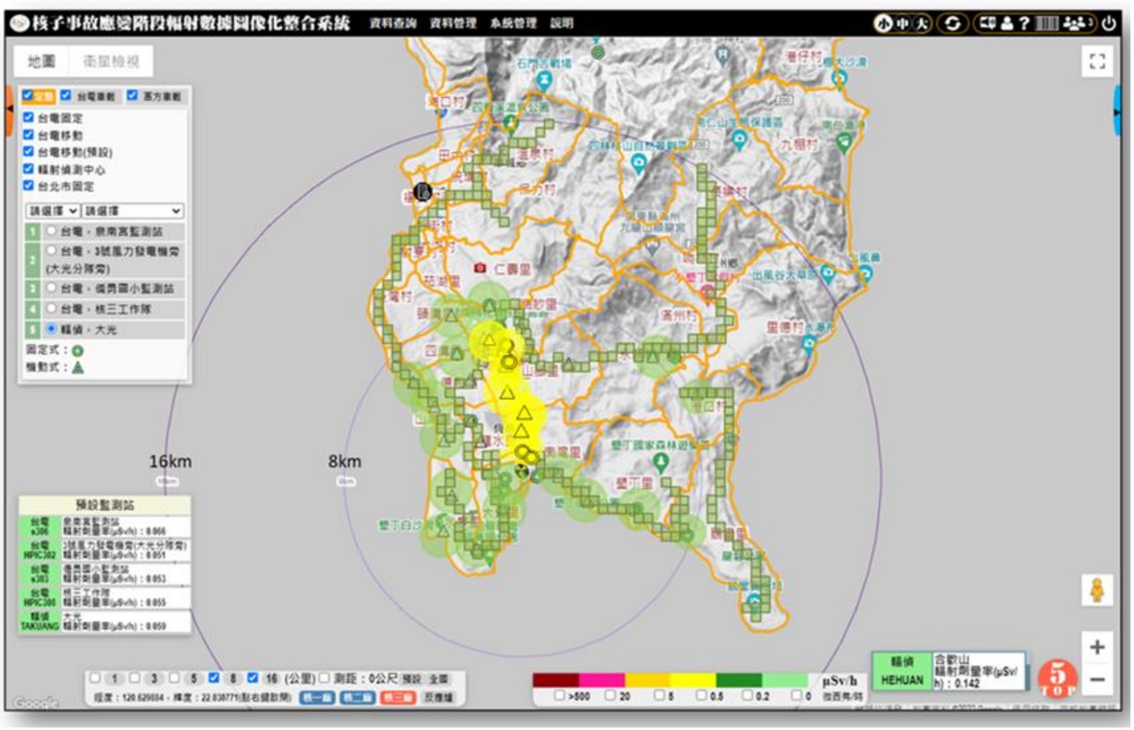

Figure 2. Real-Time Environmental Radiation Monitoring in the 2022 Nuclear Emergency Exercise

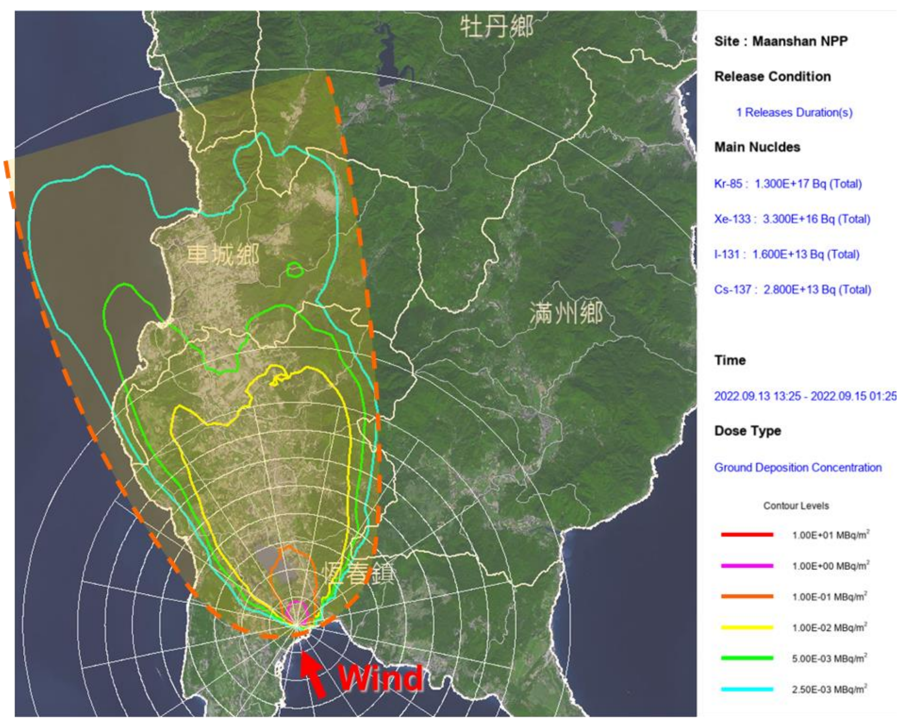

Figure 3. Predictions of the Dose Evaluation System for the 2022 Nuclear Emergency Exercise

4. CONCLUSIONS

The aim of public protective actions in a nuclear emergency is to prevent deterministic effects of acute radiation exposure and to reduce stochastic risks of chronic radiation exposure. For this purpose, it's crucial to establish a complete framework on determination of the implementation time of each protective action. In Taiwan, current mechanism includes dose evaluation system, EALs and OILs system, which is to set up a standard for decision-maker to determine the necessary actions to be taken for the public and responders in a nuclear accident. These systems are complementary to each other for CDRC to make right and quick decisions on public protective actions.

This emergency response scheme is not unchangeable and will be constantly reviewed and improved. Optimization through conduction of nuclear emergency exercise periodically and continue study on international documents to verify the availability and practicality of current measures, and the public health system can be maintained consistent with international development trends for public safety. As the competent authority of nuclear emergency in Taiwan, it is NSC's duty to guard public's health from harmed by nuclear accident. Constantly improving the emergency response scheme to ensure nuclear safety is the only way to achieve a sustainable nuclear future.

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