出國報告（出國類別：其他）

赴美國橡樹嶺國家實驗室參訪除役核設施

服務機關：核能研究所
姓名職稱：周子鑫　助理研究員
派赴國家：美國
出國期間：104 年 7 月 4 日~104 年 7 月 12 日
報告日期：104 年 8 月 12 日

摘　要

本所助理研究員周子鑫於 104 年 7 月 4 日至 7 月 12 日共計 9 天公差赴美國，其主要任務為配合未來所內相關核設施清理計畫之既存 TRU 廢棄物整檢工作需要，擬參考先進國家做法並與專家學者進行討論與交流，同時蒐集相關資訊與深入瞭解其廢棄物管理技術現況，以提供本所未來精進我國放射性廢棄物安全管理技術，確保民眾健康及環境保護等相關議題研究規劃時之參考與借鏡；並藉由本次參訪與 ORNL 研究人員建立直接聯繫管道，以利後續持續派員赴美國國家實驗室學習，及建立合作關係以提昇本所能見度。

另 ORNL 針對已完成除役之核設施，藉著植栽移植、景觀綠化，或是規劃為停車場，以達成資源最佳化、高效益之利用，營造綠色環境，頗有值得本所參考之價值。

目　　次

（頁碼）

一、目　的

公差人係奉派至美國橡樹嶺國家實驗室(Oak ridge National Laboratory, 以下簡稱為ORNL，)參訪，時間為 2015 年 7 月 04 至 2015 年 7 月 12 日。

本次參訪緣起主要有鑑於本所現有超鈾元素污染放射性廢棄物(以下簡稱 TRU 廢棄物)貯存場所之設計貯存容量有限，而早期由於我國對 TRU 廢棄物概念未如現在明確，只要發現疑似 TRU 廢棄物者均將其歸類為 TRU 廢棄物，此舉對 TRU 廢棄物倉貯實為一大負擔。故為減輕現有 TRU 廢棄物貯存庫逼近滿貯之壓力，擬針對已入貯 TRU 廢棄物進行整檢作業後再重新入庫，其中非屬 TRU 廢棄物者則另行裝桶置於其他適當廢棄物貯存場所。

故欲進行本次整檢作業前，擬參考國外先進國家相似經驗，作為本所之後處理流程之依據。因此，此次參訪重點如下：

1.澄清 TRU 廢棄物的定義

2.了解美國如何計算 TRU 廢棄物中含可分裂物質其換算為鈽-239 之相當重量

3.了解美國進行 TRU 廢棄物取出、整檢作業前，工作人員接受之相關訓練課程

4.了解 ORNL 對於整檢作業期間的作業環境要求為何?例如：採正、負壓環境；空間換氣率是多少；相關通風過濾設備有哪些特殊設計考量；作業場所內設置那些監控儀器；及現場工作人員之防護衣具；若不慎發生污染外洩事件或人員不慎吸(嚥)入含放射性物質時，要進行那些緊急應變措施，事後復原工作又要如何進行…等。

5. 了解 ORNL 對於完成整檢後，TRU 廢棄物進行再包裝之盛裝容器，有那些特殊設計要求?及後續如何進行傳送至指定區域安全貯放；爾後之監控措施又有哪些?

另希藉由本次參訪可與 ORNL 研究人員建立直接聯繫管道，以利後續人員赴美國國家實驗室學習，及建立長期合作關係，並提昇本所能見度。

二、過　程

(一) 行程及工作摘要

此次行程共計九日，七月四日啟程前往美國田納西州橡樹嶺國家實驗室(參閱圖1)，於七月十二日完成本項參訪任務返國。行程如下表所示，詳細行程紀要如下：

行程				公差地點	工作內容
日期	星期	出發	抵達	地名	
7/4	六	臺北		ORNL	去程
7/5	日		ORNL	ORNL	抵達美國田納西州
7/6-10	一-五	-	-	ORNL	參訪橡樹嶺國家實驗室並針對 TRU 議題進行討論
7/10	五	ORNL			下午完成參訪後立即返台
7/11	六	ORNL			回程
7/12	日		臺北		回程

行前，感謝原能會駐美代表趙衛武副組長透過台美民用核能合作會議，並經聯繫ORNL 促成此行。首先依據過去趙博與 DOE/EM 總部的交涉經驗，我方人員應提出簡歷並告知有關此次見習的目的，實習項目，及預計時程等資訊。因而公差人除填寫美方要求之「Unclassified Foreign National Visits & Assignments Questionnaire」資料外，並檢送本次行程參訪計畫如下：

1. Low-level and Mixed Low-level Waste Management

The experience of managing and treating of Low-level and Mixed Low-level Waste generated at ORNL, including classification criteria and regulations and storage management requirements. And what emergency measures will be taken once the accident happen. In addition, how to evaluate the impact on the environment. Besides, are there any plans in the future can make management more humanized and automation.

2. Decontamination and Decommissioning of the 2000 Complex Facilities at ORNL

The experience of decommissioning of the 2000 Complex at the ORNL where was completely decontaminated and decommissioned between spring of 2009 and winter of 2010. What is the background of the incident, and how to choose the most appropriate way of decontamination, what factors need to be considered. After decontamination is complete, what is the follow-up planning for the site...etc.

3.TRU Waste Treatment

The experiences and work procedures of the state-of-the-art treatment techniques of the TRU waste , includes on-site waste retrieval and transport to the waste treatment facility, treatment, and packaging of TRU and associated low-level radioactive waste streams for final safe off-site disposal at other facilities. And how to calculate other isotopes to equivalent weight of plutonium 239.

What type of containers used to package TRU waste, and what is the design of the packaging container. Once the contamination occurs, which

treatment methods can be taken to minimize the damage. What protective measures and equipment needs when handling. Furthermore, are there any plans in the future can make TRU treatment more safety and automation.

前述行程參訪計畫摘譯如下，我方主要提出三項主題供 ORNL 審閱，分別是(1)中、低放射性廢棄物管理：主要想了解其廢棄物分類標準、管理要求，以及當意外事故發生時應變措施為何、如何評估貯存或處理放射性廢棄物時對環境造成的影響等等，甚或未來有無計畫發展更自動化及更人性化的管理措施等；(2)除污及除役設施經驗回饋：ORNL 於 2009~2010 期間曾進行設施拆除及除役工作，想了解該背景事件原因及當時如何評估最佳除役方式和除役後場址的規畫等；(3)TRU 放射性廢棄物處理：欲了解其 TRU 處理流程為何?後續包裝、運送使用的容器及設計規範、人員的防護措施及發生意外事故如何讓損害降至最低，甚或未來有無可能發展更自動化更安全之處理設備等等。

最後獲 ORNL 同意可前往 1 周參訪，同意函如附件一。

公差人於 7 月 6 日當天先至其訪客中心由 Environmental Sciences 部門 Dr. Pierce, Eric M.協助辦理報到，領取識別證如圖 2，公差人之辦公室位於 Environmental Sciences Division (Building 1505)。隨後幾日行程則依公差人提出訓練計畫內容部分事項進行學習，因 Dr.Eric 仍有其他業務負責，無法隨時陪同公差人討論，故 Dr.Eric 先予公差人大量文獻資料供研讀(文件清單如附件三)，再針對公差人不明瞭之處進行說明。期間，並安排和 WIPP 人員 Dr. Alton D. Harris III 進行電話會議，會議中首先說明何謂 TRU：是指超過 100 nCi/克的α-輻射同位素，且半衰期大於 20 年者，並說明美國主要 TRU 來源有六個地方，分別是 Hanford、Idaho National Engineering and Environmental Laboratory (INEEL)、Rocky Flats Environmental Technology Site (RFETS)、Los Alamos National Laboratory (LANL)、Oak Ridge National Laboratory (ORNL)、Savannah River Site (SRS)。接著說明 WIPP 作為 TRU 處置場址的優點為其特殊之鹽層地理環境可將水分完全排除在外，避免當 TRU

廢棄物外洩造成污染等。WIPP 預計運轉 35 年至 2035 年後封閉，於 1999 年第一次接收 CH-TRU、2007 年第一次接收 RH-TRU。WIPP 每周接收來自全國各地 CH-TRU 平均約 21 案次、RH-TRU 平均約 5 案次，可貯存容量達 176,500 立方公尺。WIPP 處置場可分為地上設施及地下處置區：地上設施主要是在接收 TRU 廢棄物時，進行包件表面檢查；接收後，送至地下處置區依廢棄物種類分別將 CH-TRU 貯存於處置間內、RH-TRU 則橫放貯存於 WIPP 於壁上所開挖之鑽孔內(boreholes) (如圖 3)。另其所要求之包裝容器、運輸容器等規範、盛裝容器之 PE-Ci、FGE 限值等要求則於第三節詳述。最後一日，Dr.Eric 並開車載著公差人繞 ORNL 一圈，同時向公差人說明已除役及處理中各設施現況及其除役後場址規劃：ORNL 現已完成除役之核設施，大都規劃為停車場或是藉著植栽移植將景觀綠化(如圖 4)，給予工作人員一個舒適的環境。其中因參觀相關處理設施前需先聯繫該工作人員及預作訓練或配戴合適之防護衣具方能進入，惟此次行程逗留時間不長因而僅於設施門口前駐留一會兒即離去。隨後，下午即辦理出境手續搭機返國，完成本次任務。

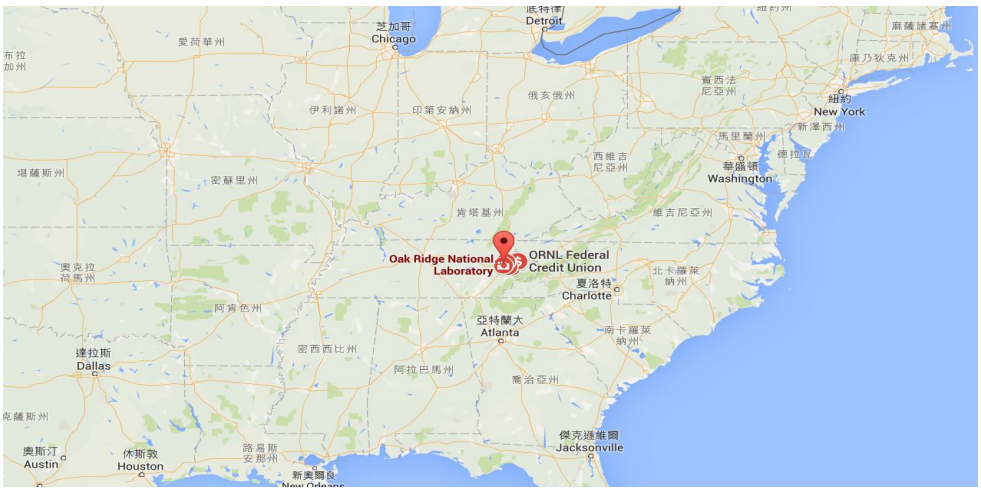


圖 1、本次公差橡樹嶺國家實驗室(圖中的紅點)之相關位置圖

圖 2、本次公差人之識別證

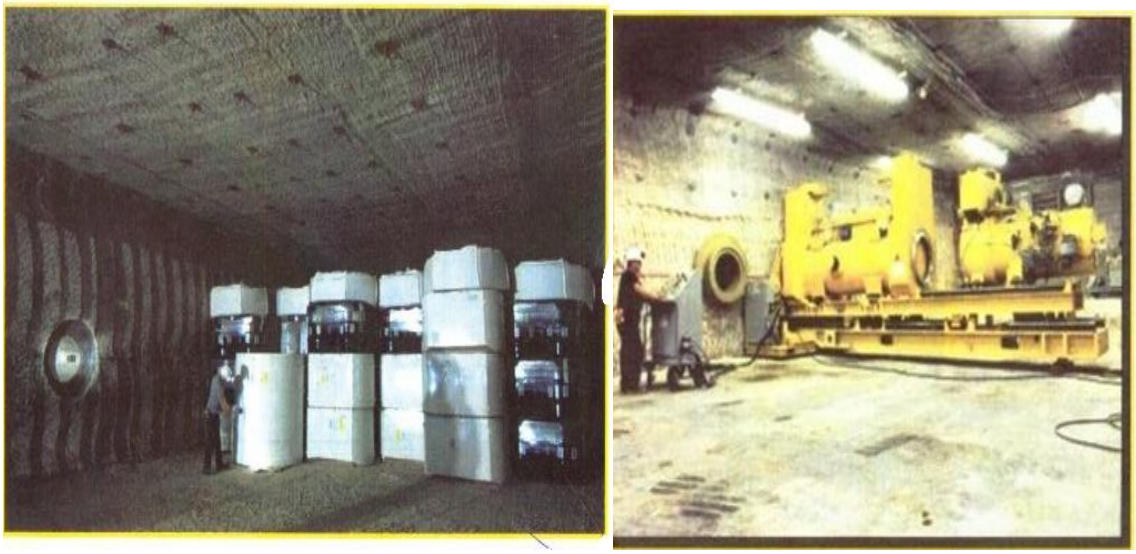


圖 3、左為 CH-TRU 處置、右為 RH-TRU 處置

圖 4、ORNL 核設施除役前後示意圖

(二) 橡樹嶺國家實驗室簡介

「橡樹嶺國家實驗室（Oak Ridge National Laboratory - 縮寫為ORNL），原稱柯林頓實驗室，是美國能源部所屬的一個大型國家實驗室，成立於 1943 年，最初是作為美國曼哈頓計劃的一部分，以生產和分離鈾和鈽為主要目的而建造。2000 年 4 月以後由田納西大學和 Battelle 紀念研究所共同管理。橡樹嶺國家實驗室為美國能源部所屬最大的科學與能源研究實驗室，每年的預算高達 16.5 億美元，其中 80%來自美國能源部，20%來自聯邦政府與民間企業。現有職員約 4,400 人，其中研究人員與工程師約 3000 人。主要研究領域包括中子科學、化學與放射化學技術、複雜生物系統、能源科學、工程科學與機器人、環境科學、高效計算、數學、測量科學、物理和化學科學、模擬科學，及國家安全等。

ORNL 的任務主要為基礎科學的研究和應用領域的開發，運用科學知識及技術以提供創新方法解決複雜問題等，維持美國在主要科學領域裡的領先地位、提高潔淨能源的效率、恢復和預防環境以及為國家安全等作出貢獻。該實驗室分布示意圖如圖 5。

圖 5、橡樹嶺國家實驗室之相關位置圖

(三) TRU 廢棄物處理技術

以下就美國對於 TRU 廢棄物之定義與分類、TRU 廢棄物之包裝、運送及貯存、及 TRU 廢棄物之接收要求，做一說明如下：

1. TRU 廢棄物之定義與分類

早期(1970)美國對於 TRU 廢棄物的定義是以 10 nCi/g 為標準。現行之美國 EPA 環境輻射防護標準 40 CFR 191 與 194 以 100nCi/克作為標準，而美國 NRC 在 10 CFR 61 的法規亦採用 100 nCi/克的一致定義。即 TRU 棄廢物定義為含超過 100 nCi/克的α-輻射同位素，且半衰期大於 20 年者。

TRU 廢棄物可再分為表面劑量率小於 2mSv/hr 之接觸處理超鈾廢棄物(contact-handled, CH-TRU)與表面劑量率大於 2 mSv/hr 但不超過 10 Sv/hr 的遙控處理 TRU 廢棄物(remote-handled, RH-TRU)兩類。

我國 TRU 定義則和美方超鈾廢棄物定義相同，為(1)原子序大於 92，(2)α比活

度大於 3700Bq/g(等同於 100 nCi/克)，(3) 半衰期大於 20 年之元素。

2．TRU 廢棄物之包裝、運送及貯存

美國 TRU 廢棄物目前都貯存在 WIPP(Waste Isolation Pilot Plant)，WIPP 位於新墨西哥州卡爾斯巴德城（Carlsbad）外奇華胡安沙漠，是世界上第一個深地層處置場。地質為具有 2.5 億年穩定的古老鹽層，TRU 貯放於地底下約 660 公尺處。因鹽層的易於開採及高阻隔水分特質，可提供處置廢棄物穩定的貯存環境達到永久隔離之目的。WIPP 內處置的 TRU 廢棄物有 96 %屬於 CH-TRU 類型，主要是α 與β 衰變核種，長半衰期的核種有 Pu-239, Pu-240, Pu-241、Am-241 及 Cm-244 等，一般作業上並不需要使用特別屏蔽加以安全處理，常使用包裝容器有標準 55 加侖鋼桶、標準廢料箱(SWB)、十桶護箱(TDOP)及 RH-TRU 廢棄物盛裝容器等。

RH-TRU 廢料因具有穿透性的伽瑪(γ)輻射，處理與運送過程必須放置於鉛或鐵屏蔽之護箱內，常見核種如 Cs-137、Ba-137、Co-60、Eu-152, Eu-154, Eu-155 等。

(1)包裝

TRU 廢棄物一般桶內或箱內會內襯聚乙烯 (polyethylene liner)進行包裝，目前所使用的包裝容器有很多種，最多使用的貯存容器為鋼製桶槽，一般是 55 加侖桶及鋼製箱體。由於 TRU 廢棄物貯存時，有機物質容易受到輻射影響裂解生成可燃氣體，故在盛裝容器設計上均有過濾器洩壓裝置以避免貯存容器內氣體壓力的累積和阻絕放射性核種逸出。

盛裝 TRU 廢棄物的包裝容器都須符合美國運輸部法規 DOT7A Type A 的規範要求。包裝容器必須是鋼製，且容器狀況必須良好未受毀損並經外觀檢查確定無任何問題。

依據 DOT 7A Type A 規範，盛裝容器認證項目包括灑水測試、自由墜落測試、堆疊測試、刺穿測試、壓力測試及震動測試，經認證合格之容器外部會標上

USA DOT 7A Type A 之標誌。

A.標準 55 加侖桶

WIPP 處置場主要包裝容器為標準 55 加侖桶(如圖6)，尺寸大小約外徑 0.61 公尺、高 0.89 公尺，盛裝體積為 208 L，由低碳鋼製造成堅硬的容器，內襯聚乙烯，頂蓋上方有一個或多個過濾功能的排氣口，可排除或防止放射性微粒逸出及消除桶內產生之氣體。

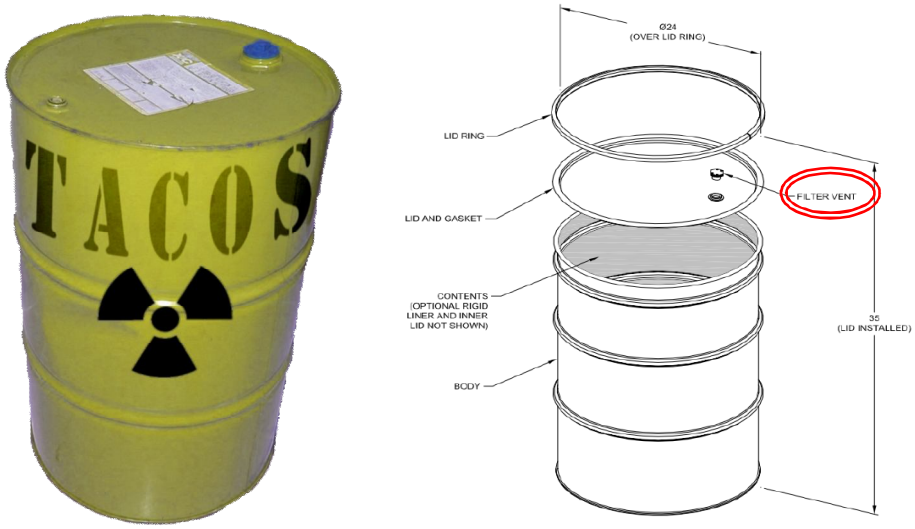


圖 6、55 加侖桶包裝容器

B.標準廢料箱(Standard waste boxes, SWB)

WIPP 處置場另外使用標準廢料箱，盛裝無法放進 55 加侖桶之大型 TRU 廢棄物，該箱體尺寸大小約外徑 1.8 公尺長 × 1.38 公尺寬 × 0.94 公尺高，體積約 1.88 立方公尺(如圖 7)。SWB 的本體亦設計有一個或多個過濾功能的排氣口，可排除或防止放射性微粒逸出和消除箱內產生之氣體，且一個 SWB 約可置入四個 55 加侖桶。

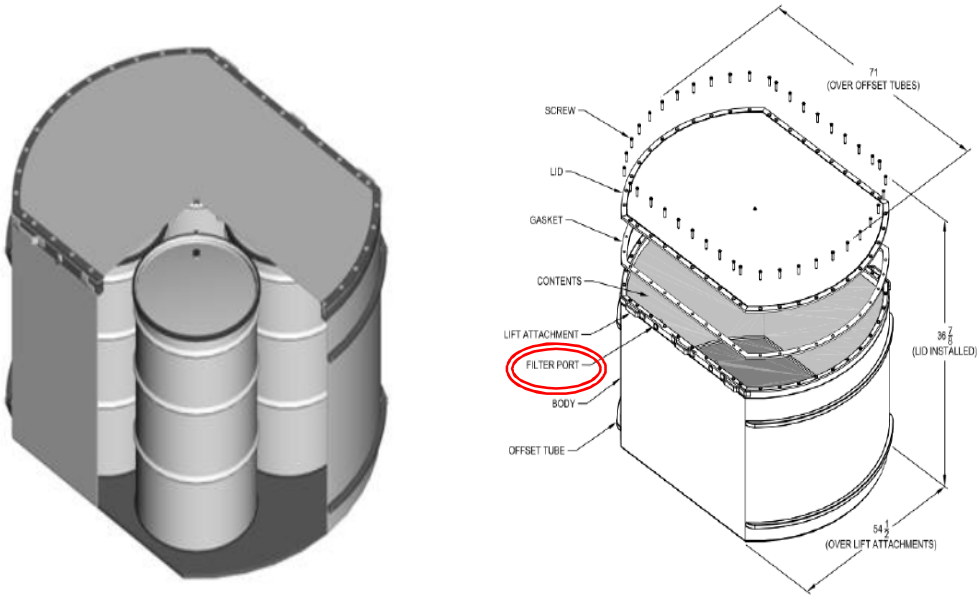


圖 7、SWB 標準廢料箱包裝容器

C.十桶外護箱(Ten-Drum Overpack, TDOP)

十桶外護箱(圖 8)為金屬製的包裝容器，為鋼鐵焊接的正圓筒形容器，尺寸大小為直徑 1.8 m 和高 1.9 m，乘載重量為 3,040 公斤，一個 TDOP 最多可裝入 10 個標準 55 加侖桶或一個 SWB。該箱體一端的螺栓蓋板為可移動式，利用蓋板與本體間 styrene-butadiene 或 neoprene 橡膠墊圈的迫緊方式達到氣密設計、靠近 TDOP 本體的頂部設置一個以上之過濾器口，以排除或防止放射性微粒逸出或消除箱內產生之氣體。本箱體可作為裝有 CH-TRU 混合廢棄物桶或 SWB 的護箱，亦可直接裝進 CH-TRU 混合廢棄物。使用本包裝容器時機有 2 點，當 TRU 廢棄物無法置於標準 55 加侖桶內或標準廢料箱時及當前述二包裝容器發生鏽蝕、破損需進行再包裝時。

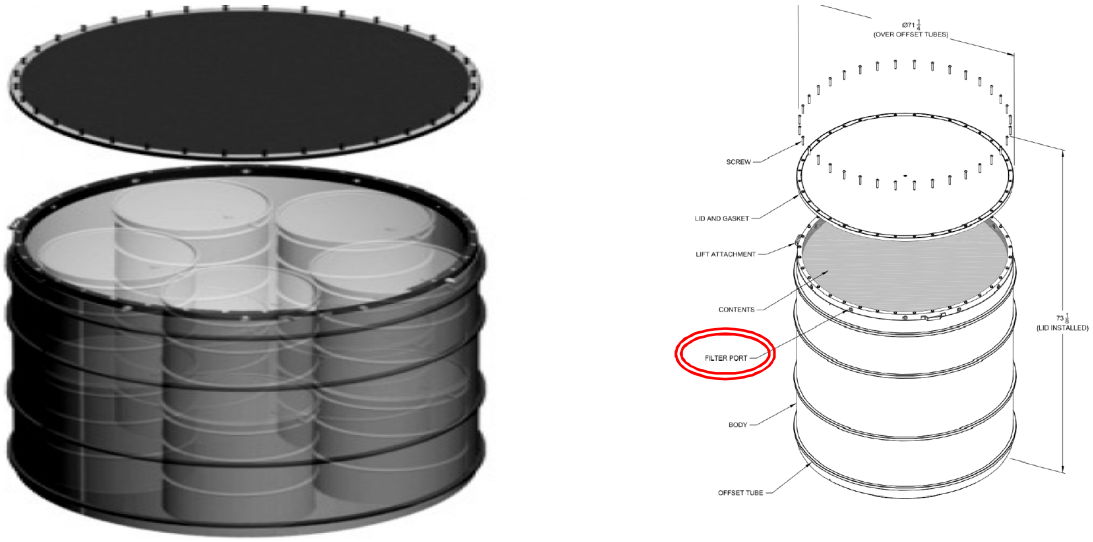


圖 8、TDOP 示意圖

D.RH-TRU 廢棄物盛裝容器

RH-TRU 的核准包裝容器僅有 55 加侖桶及 RH-TRU 廢棄物盛裝容器（如圖 9）。每只 RH-TRU 廢棄物盛裝容器尺寸大小為直徑 0.7 m 和高 3 m，可裝入三只 55 加侖桶。當裝滿 RH-TRU 之 55 加侖桶運送至 WIPP 地下處置區時，該 55 加侖桶將會被置於此 RH-TRU 廢棄物盛裝容器內並移入 WIPP 已開挖完成之鑽孔內存放。

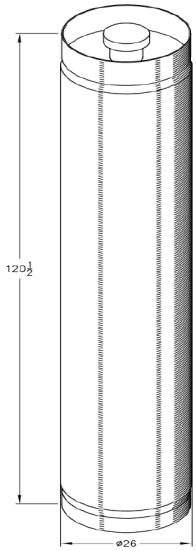


圖 9、RH-TRU 廢棄物盛裝罐示意圖

(2)運送

DOT 核可的 B 類型運送容器有三種，其中 TRUPACT II、HalfPACT 設計供 CH-TRU 的運送，RH-72B 用於 RH-TRU 的運送。此類型容器採雙層安全包裝，其設計必須承受於正常運輸條件下，暴露於華氏 100 度到華氏-40 度之間及暴露在不同外在壓力、震動或豪雨的過程中，或土石流衝擊或 5 倍運輸容器重量長達 24 小時重壓下仍能無損壞。

B 類型運送容器的認證有下列四種嚴格的測試：(如圖 10)

(A)自由掉落試驗(Free-Drop Test):將運送容器從 30 呎的高度掉落至平坦表面(如鋼筋混凝土平整表面)，測試撞擊在容器最脆弱表面的損壞程度。

(B)撞擊試驗(Puncture Test):運送容器接受一支直徑六吋，至少八吋長的鋼條，從 40 吋的高度自由落下的撞擊。

(C)燃燒試驗(Burn Test):將運送容器浸滿噴射燃油，點火燃燒使溫度達到 800℃維持 30 分鐘。

(D)浸泡試驗(Immersion Test):使用特定的分析方法，將一個相同設計的運送容器，使其接受相當於浸泡在 50 呎深水的外部壓力。

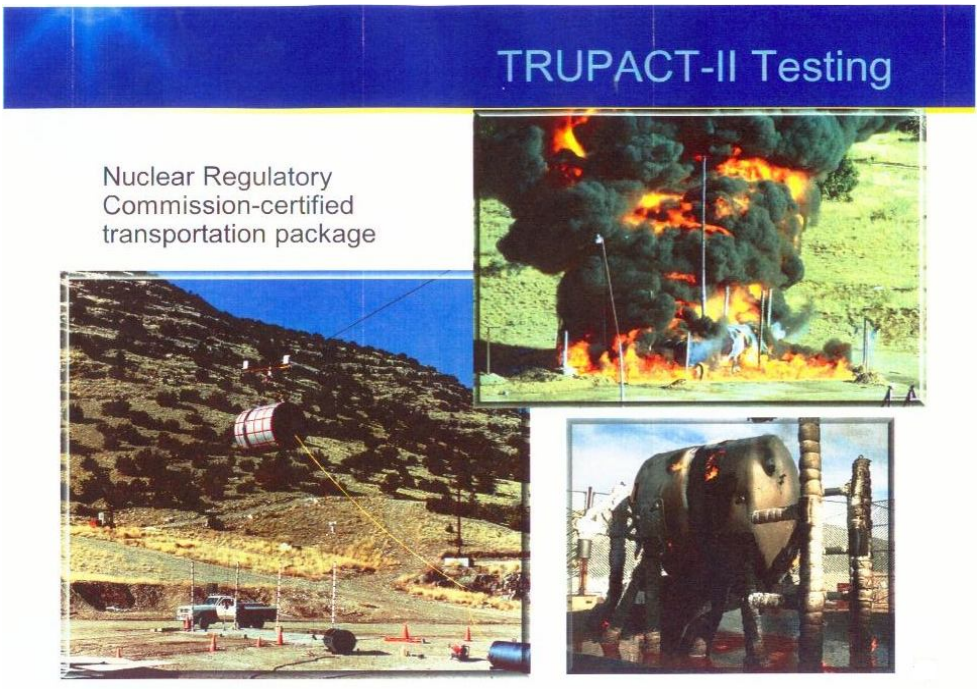


圖 10、運送容器測試實驗

A.TRUPACT-Ⅱ

TRUPACT-Ⅱ(圖 11)為圓頂頂部與扁平底部外觀的金屬容器，採用多層屏障密封容器的設計，外層為不鏽鋼材質，內層有 25 公分厚的泡棉緩衝層，並加入陶瓷纖維隔離層以強化緩衝層強度。TRUPACT-II 在車輛撞擊測試時，可承受他台汽車撞擊而無損壞；在自由跌落測試下，TRUPACT-Ⅱ撞擊跌落後仍可完好無缺；甚至在跌落試驗裡顯示，因 TRUPACT-Ⅱ上下圓頂均有蜂巢結構的防碰撞桿可發揮保護功效，可承受比高速公路平均嚴重事故的 20 倍。

TRUPACT-Ⅱ的尺寸大小為直徑約 2.5 m 和高約 3 m，一個 TRUPACT-Ⅱ可容納將近 14 個 55 加侖桶或兩個 SWB，或一個 TDOP。雖然 TRUPACT-Ⅱ型運輸容器的設計可容納 14 個 55 加侖桶，但 DOT 對於運送總重規定不可超過 36,620 公斤之限制。

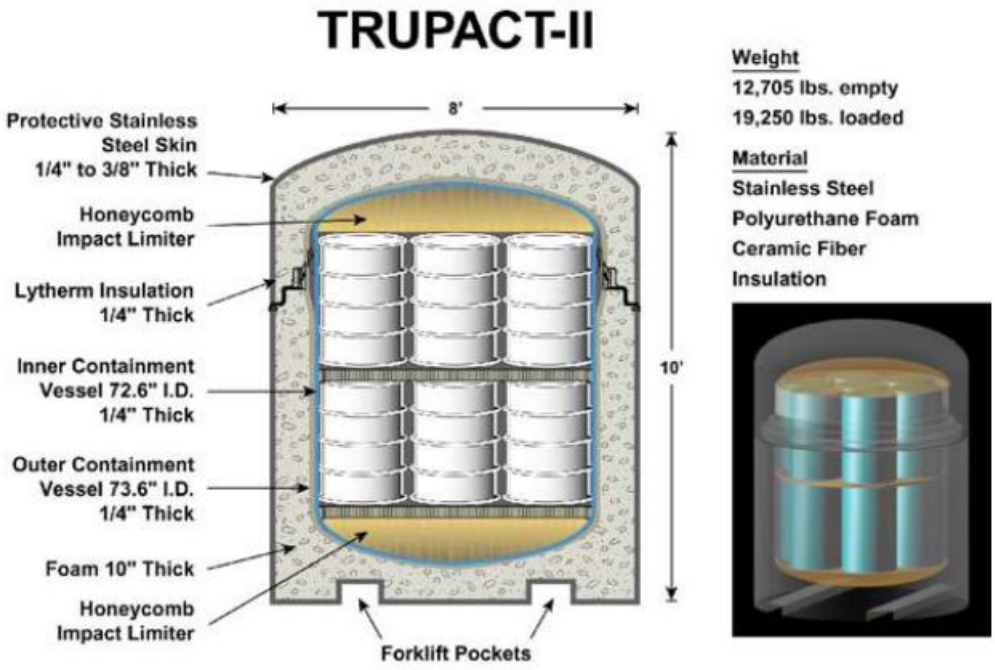


圖 11、TRUPACT-Ⅱ示意圖

B.HalfPACT

HalfPACT(圖 12)為 TRUPACT-Ⅱ縮尺版運送容器，容器的設計與 TRUPACT-Ⅱ一樣，內層有氣密設計及外層為不鏽鋼材質所構成，其尺寸大小約為直徑 2.5 公尺、高 2.25 公尺。一個 HalfPACT 設計可容納 7 個 55 加侖桶或一個 SWB。每輛 WIPP 運輸卡車最多可載運三個 HalfPACT 容器，由於使用 HalfPACT 運送容器，單次可運送更多較重的廢棄物，減少運送的次數，可降低潛在運輸事故的發生。

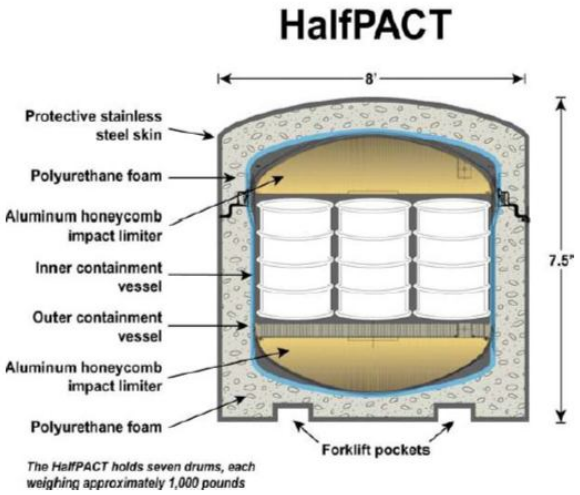


圖 12、HalfPACT 示意圖

C.RH-72B

因為 RH-TRU 表面輻射劑量率較高，必須以屏蔽容器運送，RH-72B 容器尺寸為直徑 1 公尺、長約 3.6 公尺之大圓桶，內有 5/8 吋厚的鉛內襯可有效降低人員接受輻射劑量，且如同 TRUPACT-Ⅱ及 HalfPACT 的設計，兩端充塞圓筒型避震器功能的防撞緩衝器(Impact Limiter)，外有熱絕緣層可保護容器避免潛在火災的破壞(如圖 13)。

圖 13、RH-72B 運送容器

(3)貯存

當 TRU 廢棄物運至 WIPP 處置場時，首先檢查 TRU 運送容器確認其表面污染狀態後，再將該運輸容器移至廢棄物處理大樓(WHB)，在 WHB 內之接觸處理隔間(CH bay)內有兩台 TRUPACT-Ⅱ運送容器轉載埠(TRUPACT-Ⅱ Docks, TRUDOCKs)與四座橋式起重機，可將 TRUPACT-Ⅱ及 HalfPACT 運送容器開啟，進行 CH-TRU 廢棄物的卸放。CH-TRU 混合廢棄物容器移出後，WIPP 人員先以目視檢查該包裝容器外觀情況，例如是否有無銹蝕，是否有明顯缺陷、擠壓或破裂等，以及洩漏檢查以確保貯存時良好狀態，另外廢棄物容器之表面污染亦會加以檢測。

反之包裝容器若發生前述破裂情形，此時 WIPP 人員會要求於該容器外另增加外護箱，或依 49 CFR 173 與 178 要求該包裝容器進行修補作業，甚或嚴重時將退回原產生單位。確認可安全貯放時，則將 CH-TRU 移至地下處置區進行長期貯存，WIPP 在進行貯放同時為避免放射性核種的釋出，於貯存窖廢棄物容器堆疊頂部會放置袋裝的氧化鎂吸收劑，用以吸收空浮的核種。

另如前述，在確認貯放 RH-TRU 之 55 加侖桶包裝容器外觀良好狀態時，該 55 加侖桶則會裝入 RH-TRU 廢棄物盛裝容器內後，再移入地下處置區鑽孔中，並用混擬土屏蔽塞予以安全貯存。

3.TRU 廢棄物之接收要求

根據 WIPP WAC(Waste Acceptance Criteria)，在進行 TRU 廢棄物接收時，須將可分裂物質換算為 Pu-239 之相當重量（239Pu fissile gram equivalent, FGE）、Pu-239 當量活度（239Pu equivalent curies,PE-Ci）以及熱衰減之放射性核種進行了解。

(1)Pu-239 當量活度

Pu-239 當量活度的概念是用來評估整體廢棄物內 TRU 核種的指標，因此 Pu-239 當量活度計算值可作為放射毒性危害指標。為瞭解某一特定 TRU 核種的放射性所釋放出的空浮情況，Pu-239 的量可作為轉換主要釋放空浮物質之參考依據。為了解兩者之間的關係，將以 50 年有效全身劑量之接受當量或劑量轉換因子作為其每一 TRU 核種吸入的基準點。

Pu-239 當量活度的計算是用特定 TRU 核種的加權因子來估計放射性劑量以及核種的分佈，Pu-239 當量活度(AM)之計算公式如下：

$$AM = \sum_{i=1}^{K} \frac{A_i}{WF_i}$$

K 為 TRU 放射性核種的數目，Ai 為某放射性核種之活度，WFi 則是某放射性核種之 PE-Ci 加權因子。WFi 之定義如下：

$$WF_i = \frac{E_o}{E_i}$$

其中 Eo （rem/mCi）是指 Pu-239 在 1.0 mm 活度中位數空氣動力直徑（aerodynamic diameter, AMAD）之微粒，和每週肺部吸入限值等級之 50 年有效全身劑量接受當量；Ei 則是指某放射性核種在 1.0 mm 活度中位數空氣動力直徑（AMAD）之微粒，和每週肺部吸入限值等級之最高 50 年有效全身劑量接受當量。常見的超鈾核種之加權因子,WFi 如圖 14 所示。

Table PE-Ci Weighting Factors for Selected Radionuclides

Radionuclide	Pulmonary Clearance Class[1]	Weighting Factor
^{233}U	Y	3.9
^{237}Np	W	1.0
^{236}Pu	W	3.2
^{238}Pu	W	1.1
^{239}Pu	W	1.0
^{240}Pu	W	1.0
^{241}Pu	W	51.0
^{242}Pu	W	1.1
^{241}Am	W	1.0
^{243}Am	W	1.0
^{242}Cm	W	30.0
^{244}Cm	W	1.9
^{252}Cf	Y	3.9

[1](W) Weekly, (Y) Yearly

圖 14、常用超鈾核種 WFi 值

(2)可分裂物質換算為 Pu-239 之相當重量

$$\text{Pu-239 FGE} = \sum_{i=1}^{K} Ai / WFi$$

公式如上，Ai 為 i 放射性核種之克當量重，圖 15 為我國常見超鈾核種之放射性比度；另經文獻可得知 Am-241 和 Pu-239 其加權因子(WFi)是 1.0，而本所 TRU 廢棄物主要放射性核種為此二核種，因而藉由該公式即可算出其 FGE 值。

放射性物質安全運送規則 60.12.15 原能會發布

核種	放射性比度(Ci/g)
Am-241	3.24
Cs-137	$9.82*10$
Co-60	$1.14*10^{3}$
Pu-238	$1.68*10$
Pu-239	$6.1*10^{-2}$
Pu-240	$2.27*10^{-1}$
Pu-241	$1.14*10^{2}$
Pu-242	$3.9*10^{-3}$
U-233	$9.5*10^{-3}$
U-238	$3.33*10^{-7}$
U-235(100%)	$2.14*10^{-6}$
Th-232	$1.11*10^{-7}$
Sr-89	$2.88*10^{4}$
Sr-90	$1.45*10^{2}$

圖 15、常用超鈾核種放射性比度值

(3)盛裝容器限值要求

每一 TRU 廢棄物盛裝容器內所含之換算為 Pu-239 之相當重量(FGE)、Pu-239 當量活度(PE-Ci)均有限值要求，分別如圖 16~圖 20 所示。

另本所廠內接收要求為廢棄物中所含可分裂之同位素換算為 Pu-239 時不得大於下列臨界數據 ：

A.55 加侖桶不得大於 200 克

B.箱型容器中每立方公尺不得大於 175 公克，總重量不得大於 350 公克

Payload Container	Packing Configuration	PE-Ci Limit
55-, 85-, and 100-gallon drum	Direct loaded – all approved waste forms other than solidified/vitrified waste	≤80 PE-Ci
Shielded Container	Direct loaded – vented 30-gallon inner steel drum – all approved waste forms other than solidified/vitrified waste	≤80 PE-Ci
SLB2	Direct loaded – all approved waste forms other than solidified/vitrified waste	≤560 PE-Ci
SWB	Direct loaded (or a bin) – all approved waste forms other than solidified/vitrified waste	≤560 PE-Ci
TDOP	Direct loaded – all approved waste forms other than solidified/vitrified waste	≤800 PE-Ci
85-gallon drum	Overpacking an undamaged[1] 55-gallon drum – all approved waste forms other than solidified/vitrified waste	≤1100 PE-Ci
SWB, TDOP	Overpacking an assembly of undamaged[1] 55- or 85-gallon drums with no single payload container within the assembly exceeding 1100 PE-Ci – all approved waste forms other than solidified/vitrified waste	≤1200 PE-Ci
TDOP	Overpacking an undamaged[1] SWB – all approved waste forms other than solidified/vitrified waste	≤1200 PE-Ci
Pipe Overpacks (Standard, S100, S200, and S300)	All approved waste forms	≤1800 PE-Ci
All	Solidified/vitrified waste	≤1800 PE-Ci

[1]An undamaged container provides an additional barrier should a breach occur in the overpack. When overpacking one or more damaged waste containers, direct loaded PE-Ci limits apply.

圖 16、CH-TRU 廢棄物包裝容器 PE-Ci 限值

Payload Container	Packing Configuration	PE-Ci Limit
RH-TRU Waste Canister 55-Gallon Drum (shipped in a 10-160B)	All approved waste forms other than solidified/vitrified waste	≤ 240 ≤ 80
RH-TRU Waste Canister 55-Gallon Drum (shipped in a 10-160B)	Solidified/vitrified waste	≤ 1800

圖 17、RH-TRU 廢棄物包裝容器 PE-Ci 限值

Payload Contents	^{239}Pu FGE Limit (Removable/Welded Lid Canister)	^{239}Pu FGE Limit (Neutron Shielded Canister)
Non-Machine-Compacted Waste		
Be/BeO limited to ≤ 1% by weight of the waste	≤ 315	≤ 245
Be/BeO limited to ≤ 1% by weight of the waste including credit taken for ≥ 5g of ^{240}Pu Poisoning[1]	≤ 325	≤ 245
Be/BeO limited to ≤ 1% by weight of the waste including credit taken for ≥ 15g of ^{240}Pu Poisoning[1]	≤ 350	≤ 245
Be/BeO limited to ≤ 1% by weight of the waste including credit taken for ≥ 25g of ^{240}Pu Poisoning[1]	≤ 370	≤ 245
Be/BeO > 1% by weight of the waste and is chemically or mechanically bound to the fissile material	≤ 305	Unauthorized
Be/BeO > 1% by weight of the waste and is not chemically or mechanically bound to the fissile material	≤ 100	Unauthorized
Machine-Compacted Waste		
Be/BeO limited to ≤ 1% by weight of the waste	≤ 245	≤ 245
Be/BeO > 1% by weight of the waste	Unauthorized	Unauthorized

[1]The minimum ^{240}Pu content for the RH-TRU waste canister shall be determined after the subtraction of two times the error.

圖 18、RH-TRU 廢棄物運輸容器 RH-72B 之 FGE 限值

FGE Limits with No Credit for Pu-240 Poisoning				
Contents	**Payload Container**	**Fissile Limit per Payload Container (Pu-239 FGE)①**	**Fissile Limit per TRUPACT-II Package (Pu-239 FGE)**	**Fissile Limit per HalfPACT Package (Pu-239 FGE)**
Not machine compacted with ≤ 1% by weight Be/BeO	Drum	200	325	325
	Pipe Overpack	200	2,800	1,400
	SWB	325	325	325
	TDOP	325	325	NA③
Not machine compacted with > 1% by weight Be/BeO	Drum	100	100	100
	Pipe Overpack	200	2,800	1,400
	SWB	100	100	100
	TDOP	100	100	NA③
Machine compacted with ≤ 1% by weight Be/BeO	Drum	200	250	250
	Pipe Overpack	Unauthorized	Unauthorized	Unauthorized
	SWB	250	250	250
	TDOP	250	250	NA③
Machine compacted with controls② and ≤ 1% by weight Be/BeO	Drum	200	325	325
	Pipe Overpack	Unauthorized	Unauthorized	Unauthorized
	SWB	Unauthorized	Unauthorized	Unauthorized
	TDOP	Unauthorized	Unauthorized	NA③
Machine compacted with > 1% by weight Be/BeO	Drum	Unauthorized	Unauthorized	Unauthorized
	Pipe Overpack	Unauthorized	Unauthorized	Unauthorized
	SWB	Unauthorized	Unauthorized	Unauthorized
	TDOP	Unauthorized	Unauthorized	NA③

FGE Limits with Credit for Pu-240 Poisoning		
Contents	**Minimum Pu-240 Content in Payload (grams)**	**Fissile Material Limit per Package (Pu-239 FGE)**
Not machine compacted with ≤ 1% by weight Be/BeO in drums or SWB(s)	5	340
	15	360
	25	380

Notes:

① The FGE limit given applies to the payload container regardless of Pu-240 content in the package.

② The contents shall be machine-compacted waste in the form of "puck" drums and meeting the conditions specified in Section 3.1.1

③ Not applicable.

圖 19、CH-TRU 廢棄物包裝容器 FGE 限值

FGE Limits with No Credit for Pu-240 Poisoning		
Contents		**Fissile Limit per RH-TRU Canister (Pu-239 FGE)**
Not machine compacted with ≤1% by weight Be/BeO		315
Not machine compacted with >1% by weight Be/BeO (chemically or mechanically bound)		305
Not machine compacted with >1% by weight Be/BeO (not chemically or mechanically bound)		100
Machine compacted with ≤1% by weight Be/BeO		245
Machine compacted with >1% by weight Be/BeO		Unauthorized
FGE Limits with Credit for Pu-240 Poisoning		
Contents	**Minimum Pu-240 Content in RH-TRU Canister (grams)**	**Fissile Limit per RH-TRU Canister (Pu-239 FGE)**
Not machine compacted with ≤1% by weight Be/BeO	5	325
	15	350
	25	370

圖 20、RH-TRU 廢棄物包裝容器 FGE 限值

三、心　得

(一). 本次國外公差旨在學習美國如何處理 TRU 放射性廢棄物的流程，雖然沒有實際前往美國現正運轉中之 TRU 廢棄物處置場 WIPP，但是負責接待的 Dr.Eric 仍是十分盡心的努力安排議題，及提供相當多文獻供公差人研讀及參考。期間，若有任何疑問之處，Dr. Eric 在其了解範圍內會盡量解釋清楚至公差人完全了解；若有些問題非其所涉獵者，Dr.Eric 也會想辦法透過管道向專門負責該領域之人員尋求解決。讓公差人對美方如此盡心負責安排此次行程，及美方處事如此有條不紊留下深刻印象。

(二). 本次公差回國後，再重新回顧本所接收 TRU 放射性廢棄物之相關規定，愈加了解當初制定該規定之來龍去脈，也清楚了其中所需資料 FGE 及 PE-Ci 的計算方式及重要性，實則對本所往後管理 TRU 廢棄物十分有所助益。尤其在配合本所未來清理計畫執行下，相關包裝容器的要求及管制，運送容器的使用，可供本所參考依循。

(三). ORNL 現已完成除役之核設施，藉著植栽移植、景觀綠化，或是規劃為停車場，以達成資源最佳化、高效益之利用，也營造綠色環境，頗有值得本所參考之價值。蓋植栽的使用具有積極的固碳效果。相關研究指出，闊葉大喬木每平方公尺 1 年能減少 900 公斤的二氧化碳，每半世紀就能吸收 45,000 公斤的二氧化碳；綠牆及綠圍籬每年每平方公尺亦可降低 100 公斤的二氧化碳排放量，不僅可減少水污染亦達美化環境之效。

(四). 輻射是看不到也摸不見的，然而它對人體所造成的傷害卻不亞於任何一種疾病。因而在處理相關放射性廢料時，如若能考慮的越謹慎與周密，相對

的意外事故災害的發生就能降至最低，這對本所內、外環境及人民而言都是一大福祉，而此端賴著相似經驗的交流與回饋方能避免。台美民用核能合作會議就為此提供了一個非常良好的平台。透過參與相關之國際交流，可以吸取國外最新之經驗與資訊，有助於解決各項研究發展計畫上所遭遇的實際問題。彼此之經驗得以直接溝通與交流，使參與人員皆有實質之收穫。

四、建 議 事 項

(一). 這次前往 ORNL 主要是針對 TRU 廢棄物相關處理貯存進行討論，期間 Dr.Eric 也有安排和 WIPP 人員進行電話會議，初步對 TRU 處理情形做個說明!如果可以的話，未來建議可安排前往 WIPP 實際觀摩學習。

(二). 此次行程較可惜的是無法參觀相關處理或已除役之核設施，像是 High Flux Isotope Reactor, HFIR、石墨反應器(graphite reactor)、Y-12 Plant、K-25 Plant 等等。雖然 Eric 有帶我至設施門口並稍作解說，惟因進入這些相關設施需先聯繫相關工作人員及預作訓練，而此次行程逗留時間並不長因而無法參觀，未來建議若有機會前往可預作安排。

(三). 近年來，本所有經驗的專業技術人員陸續退休，造成嚴重的人才斷層。然而，核能發展的腳步是一直往前的，透過國際間的研討交流，可確實縮短摸索的時期，培養具有國際觀之年輕研發人力。建議核能研究所應積極鼓勵同仁參與各項國際活動並發表所內最新成果來提升我國的學術地位，增進核能研究所的國際聲譽。

五、附錄

附件一、邀請函

附件二、WIPP 電話會議簡報

附件三、赴 ORNL 攜回之文件清單

附件一、邀請函

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

P.O. Box 2008
Oak Ridge, TN 37831-6417
(865) 241-3645

April 2, 2015

Dear Tzu-Hsing Chou:

To help ensure that you receive the appropriate business visa on entry to the United States (U.S.), please provide this official invitation letter to the U.S. Border Agent upon entry to the U.S.

NOTE: Business or professional visa required for ALL non-U.S. citizens visiting the Oak Ridge National Laboratory.

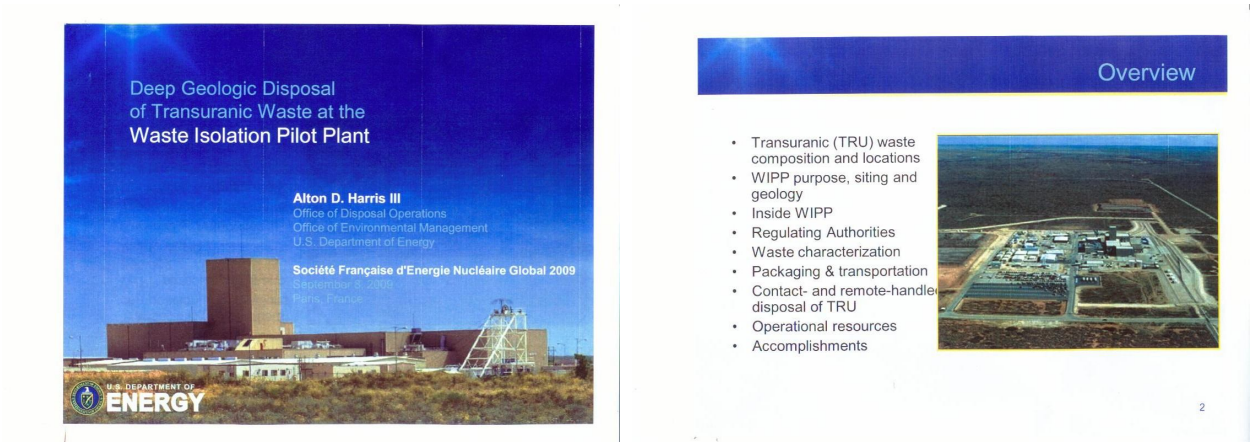
Tzu-Hsing Chou is entering the U.S. at the invitation of the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, to conduct business activities of attending and fully participating in ORNL business and scientific meetings, and conducting research at ORNL, during the period of July 4 through July 12, travel time is July 4 and 5, work time July 6 through 10 and travel time back to Taiwan July 11 through 12. The Entry Stamp should reflect either **B-1 or VWB** entry status, as appropriate, in order for Tzu-Hsing Chou to conduct the described business activities at a federal installation.

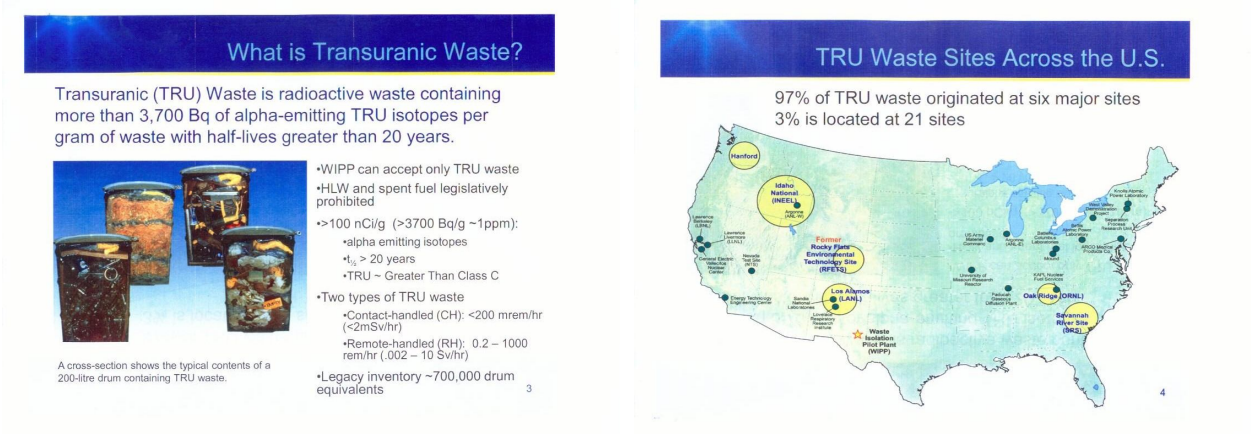
It is the visitor's responsibility to communicate with staff at the embassy or consulate issuing the visa (if necessary) and to the Agent at the point of entry into the U.S. that the purpose of the visit is to conduct business. If asked about touring or sightseeing once in the U.S., the answer should be "no, the purpose of my visit is to conduct business at the Oak Ridge National Laboratory." Before leaving the consulate and the Agent at the point of entry, the visitor must ensure that the Form I-94 or the passport visa stamp references B-1 or VWB and NOT B-2 or VWT. If the Agent made an error, request a correction so that the document(s) reflect B-1 / VWB status.

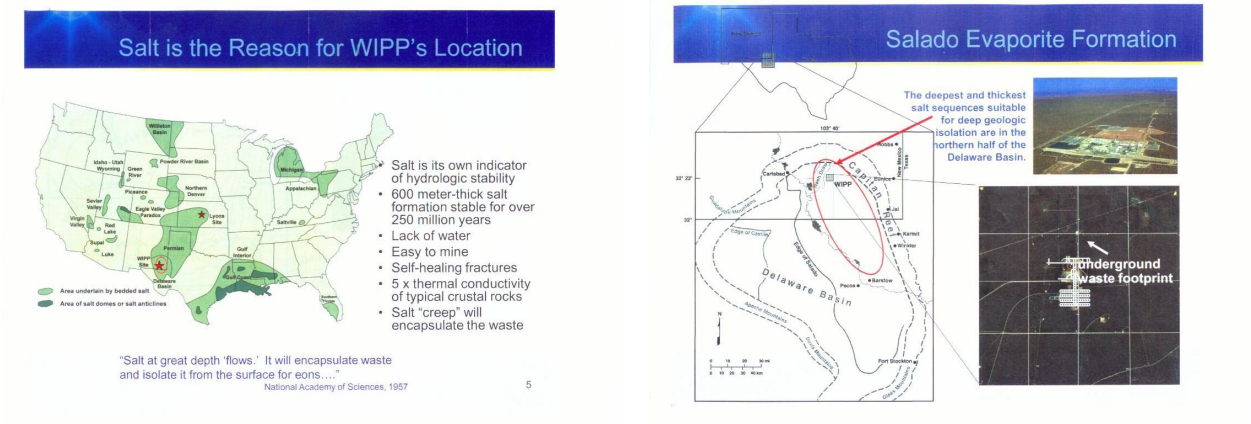
Individuals who enter the U.S. on a tourist visa (B-2 or VWT) cannot participate in the Laboratory activities beyond the level of someone coming by for a tour or a short meeting. Many come from countries where the visa waiver program is active (list below) and as you arrive at your U.S. point-of-entry you must declare that you are coming on business - not for tourism. Unfortunately, customs officers sometimes incorrectly identify you as entering as a tourist. This causes endless problems, and if you are going to be at the Laboratory working in any capacity or expecting payment or reimbursement it will be necessary to go to Nashville International Airport, stand in line and get your visa changed – an inconvenience – or worse – to both you and the Laboratory. It is essential therefore that you have at the top of your mind as you meet the immigration officer that you are entering for business purposes and that you verify that your visa or I-94 is correctly identified as business (B-1 or VWB) **before** leaving the officer and entering the U.S.

As a consequence of changing U.S. Law, it is essential that all foreign national students, scientists, and technicians working at Oak Ridge National Laboratory report to the Visitor Center with either an appropriate long-term professional or student visa (i.e., J-1, F-1, H-1, or LPR) or on a business visa (i.e.,B-1 or VWB).

附件二、WIPP 電話會議簡報







WIPP is the Safe Disposal Solution

- The Waste Isolation Pilot Plant is the United States' deep geologic repository for the safe and permanent disposal of TRU waste inventories.
- Located approximately 42 kilometers (26 miles) east of Carlsbad, New Mexico.
- WIPP received its first shipment of CH-TRU in 1999, and RH-TRU in 2007.

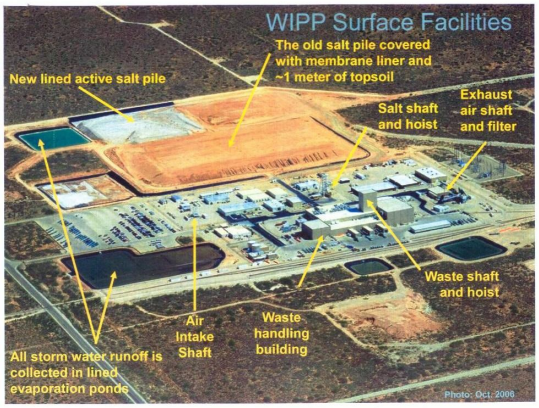
7

WIPP's Operational Capacity

- WIPP will operate 35 years until 2035
- The Land Withdrawal Act sets disposal capacity at 176,500 m^3 (6.2 million ft^3)
- WIPP receives an average 5 shipments RH-TRU per week
- Average 21 shipments CH-TRU per week
- The American Recovery and Reinvestment Act of 2009 accelerates shipments

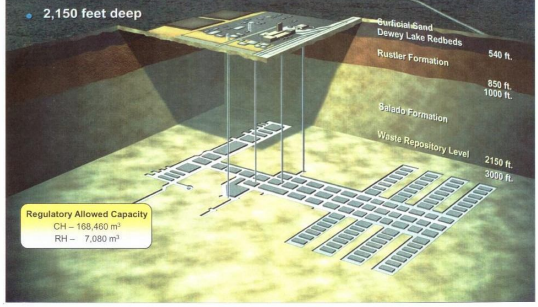
8

WIPP Surface Facilities

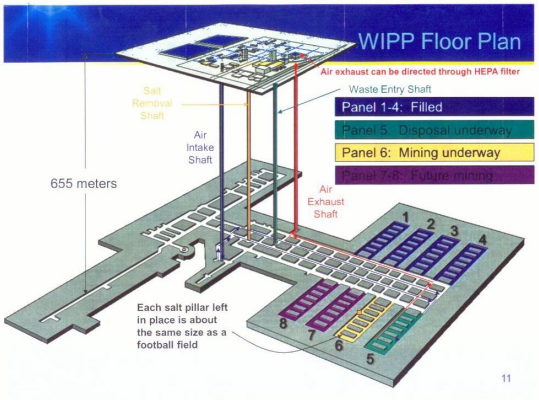


WIPP Lies 655 meters Below Ground

- U.S. Department of Energy facility
- Designed for permanent disposal of transuranic radioactive waste
- 2,150 feet deep

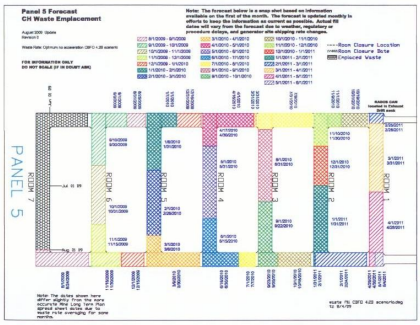


WIPP Floor Plan



11

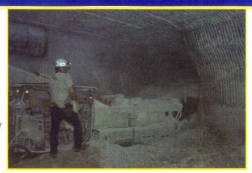
Plan View of a Waste Panel



12

Mining

- Mining completed by machine in Permian salt formation
- Panel 5 approved for use by NMED in 2008
  - ~48,000 m^3 (1.7 million ft^3) of new mining
  - ~1,200 meters (4,162 ft) of new drifts
  - First panel mined west of main access drifts
- Panel 6 mining currently underway



Roof bolts stabilize the ceiling during excavation and drum emplacement. These are monitored for salt movement and adjusted as needed.

3

Regulating Authorities

- WIPP is regulated by Federal and State of New Mexico agencies including…
  - U.S. Environmental Protection Agency
  - New Mexico Environmental Department
  - U.S. Nuclear Regulatory Commission
  - U.S. Department of Transportation
  - Mine Safety & Health Administration
  - Occupational Safety & Health Administration

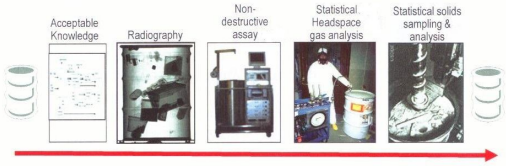
14

Regulatory Highlights

- Compliance Recertification Application
  - Required every five years until closure
  - CRA documents continued compliance with long-term disposal regulations
  - Submittal to the Environmental Protection Agency by March 26, 2009
  - Recertification determination may take 12-15 months
- Hazardous Waste Facility Permit Renewal Application
  - Ten-year permit issued in October 1999
  - Renewal application delivered to the New Mexico Environment Department on May 28, 2009

15

The Dance of the Drums—Packaging and Characterization

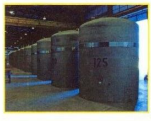


- Payload containers nominally move 10–20 times before assembly into packages for final shipment to WIPP
- $2,000-$10,000 USD per container depending on waste type and AK pedigree
- All operations audited annually by CBFO with regulatory scrutiny
- Mistakes here result in regulatory compliance orders and penalties

16

NRC-licensed Shipping Packages

TRUPACT-II

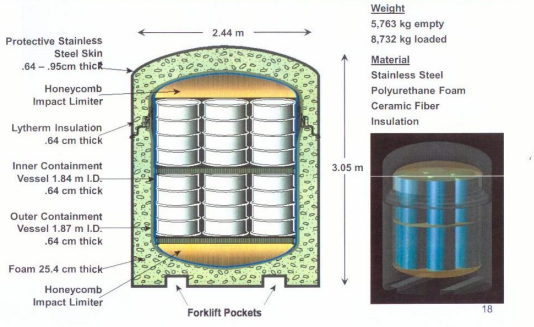


CNS 10-160B

RH-72B

17

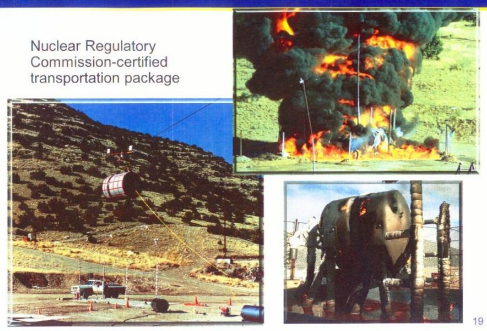
TRUPACT-II



18

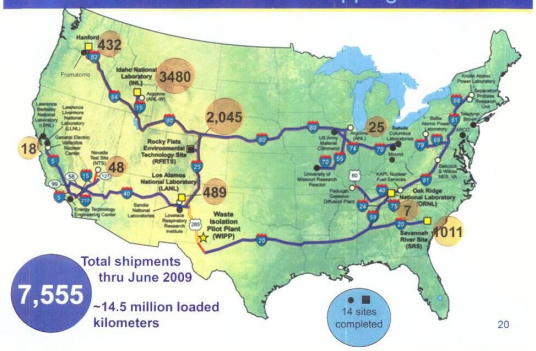
TRUPACT-II Testing

Nuclear Regulatory Commission-certified transportation package



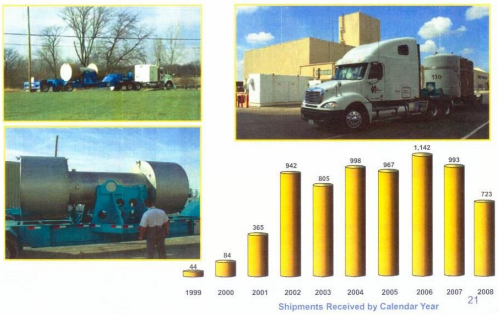
19

U.S. Shipping Corridors



20

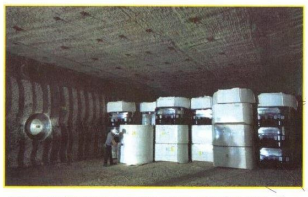
CH- and RH-TRU is Transported to WIPP by Truck



21

CH Disposal

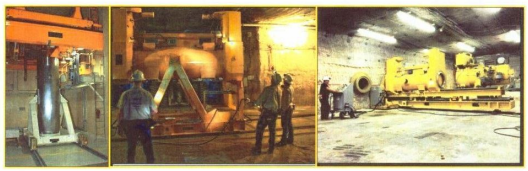
Waste containers are unloaded and lowered 655 meters underground for final emplacement



Waste is emplaced in rooms mined out of ancient saltbeds. Magnesium oxide is placed on waste stack to limit solubility of radionuclides (engineered {chemical} barrier)

22

RH Disposal



Remote Handled waste canisters are pulled from the shipping cask behind shield doors and placed into a shielded facility cask for handling at WIPP

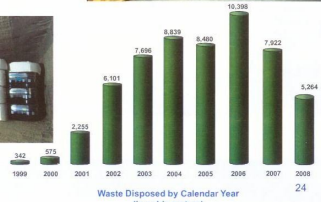
In the underground, the facility cask is removed from the hoist and transported to a disposal room by a 37-metric ton (41 ton) fork lift

RH waste in the canister is emplaced in boreholes pre-drilled into the walls of disposal rooms, and a concrete shield plug is inserted afterwards

23

CH- and RH-TRU Disposal

- CH placed for disposal on the drift floor
- RH placed for disposal within the walls



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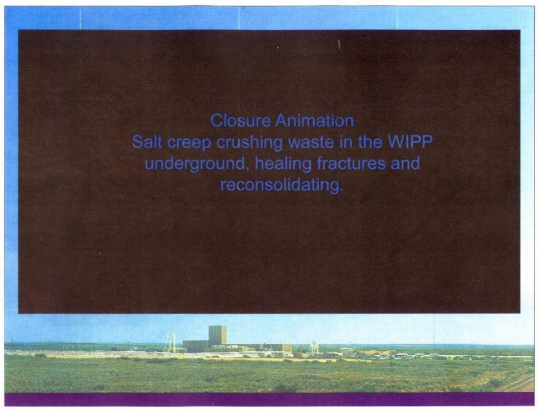


People and Equipment

- 40 tractor trucking fleet (2 private carriers)
- 112 shipping containers (84+15+12+1)
- 5 mobile characterization lines deployed at TRU sites
- 1000+ employee workforce:
  - 50 DOE Carlsbad Field Office
  - 45 Carlsbad Field Office Technical Assistance contractor
  - 38 Los Alamos National Laboratory-Carlsbad
  - 75 Sandia National Laboratories-Carlsbad
  - 630 Washington TRU Solutions (M&O contractor)
  - 162 WTS subcontractors (records, security, environmental, information systems)

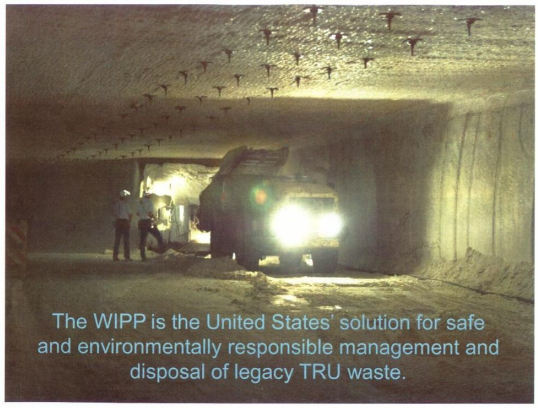
26

Snapshot (through June 2009)

- 10+ years of operation
- 7,555 shipments received
- ~300,000 loaded drum equivalent containers disposed
- Over 60,000 m^3 TRU waste disposed
- ~14,484,096 km (9,000,000 loaded miles)
- ~4 waste panels filled and closed
- 14 DOE storage sites cleaned of legacy TRU waste
- Zero releases to the environment
- Zero contaminated personnel

22 consecutive years as New Mexico "Mine Operator of the Year"

27



Backup

Title 40 U.S. Code of Federal Regulations– Protection of Environment

Part 191 - Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes

Subpart A - Environmental Standards for Management and Storage
Subpart B - Environmental Standards for Disposal
191.13. Containment requirements

a) Disposal systems … shall be designed to provide a reasonable expectation, based upon **performance assessments**, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from **all significant processes and events** that **may affect the disposal system** shall be **less than specified releases limits**

191.14. Assurance requirements
191.15. Individual protection requirements
Subpart C - Environmental Standards for Ground-Water Protection

30

40 CFR 191 (continued)

40 CFR 191.13.a Disposal systems … shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from **all significant processes** and events that may affect the disposal system shall be less than specified releases limits.

Features, events, and processes (FEPs) FEPs are screened according to:

- Probability: If probability of FEP $<10^{-4}$ in 10,000 years it is not included in PA (e.g., meteorite impact)
- Consequence: if FEP is beneficial to performance or is not relevant to WIPP it is not included in PA (e.g., sorption, ocean rise).
- Regulation: Certain FEPs are either screened in or out by regulation (e.g., mining, resource extraction following drilling).

Expected FEPs are included in all scenarios, e.g.,
- Creep closure
- Brine flow
- Gas generation

Disruptive FEPs only included in disturbed scenarios, e.g.,
- Drilling
- Mining
- Brine pocket

31

40 CFR 191 (continued)

40CFR191.13.a Disposal systems … shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that **may affect the disposal system** shall be less than specified releases limits

24 Conceptual Models Used in WIPP PA

1. Disposal system geometry
2. Culebra hydrogeology
3. Repository fluid flow
4. Salado
5. Impure halite
6. Salado interbeds
7. Disturbed rock zone
8. Actinide transport in Salado
9. Units above the Salado
10. Dissolved transport in Culebra
11. Colloidal transport in Culebra
12. Exploration boreholes
13. Cuttings & Cavings
14. Spallings
15. Direct brine release
16. Castile and brine reservoir
17. Multiple intrusions
18. Climate change
19. Creep closure
20. Shafts and shaft seals
21. Gas generation
22. Chemical conditions
23. Dissolved actinide source term
24. Colloidal actinide source term

32

40 CFR 191 (continued)

40CFR191.13.a Disposal systems … shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall be **less than specified releases limits**

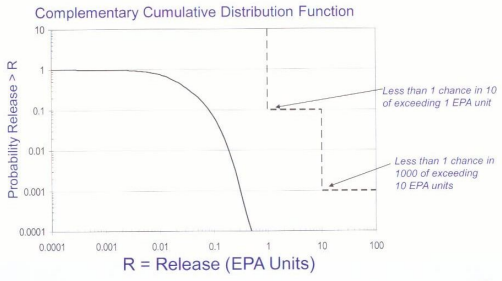
Release limits normalized by radionuclide and by total inventory

$$R = \sum \frac{Q_i}{L_i}\left(\frac{1\times10^6\ curies}{C}\right)$$

R = Normalized release in "EPA units"
Q_i = 10,000-year cumulative release (in curies) of radionuclide i
L_i = Release Limit for radionuclide i
C = total transuranic inventory (curies of α emitters $t_{1/2}$ > 20 years)

33

Release Limits: CCDF is a Measure of Compliance



34

Process Models Implement and Combine Conceptual Models

Subsurface brine and gas flow

Radionuclide transport in the subsurface

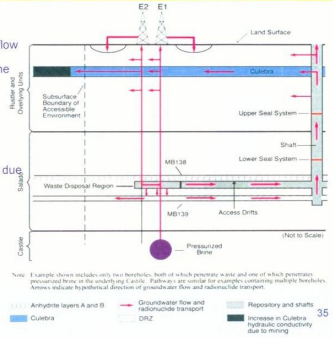
Gas generation

Brine and solids flow up a borehole

Permeability enhancement due to fracturing

Room closure

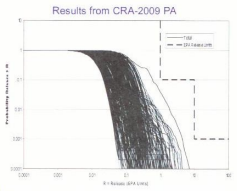
Solid extraction by drilling

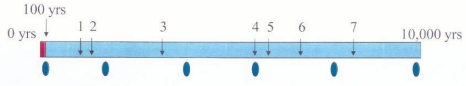


35

10,000 Possible Futures are Generated for Each Vector

- Each future consists of a series of randomly occurring drilling intrusions.
- The consequences of drilling intrusions are calculated by interpolating between consequences at discrete times.
- The cumulative release from one possible sequence of events from 0 to 10,000 years is called a future.

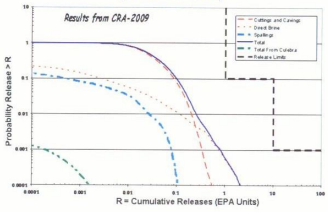




36

WIPP Compliance Posture

Disturbed Performance
(human intrusion)



Undisturbed
Performance

Release = 0

37

附件三、赴 ORNL 攜回之文件清單

項次	文件名稱
1	TRANSURANIC WASTE ACCEPTANCE CRITERIA FOR THE WASTE ISOLATION PILOT PLANT
2	International perspective on repositories for low level waste
3	Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant：Final Report
4	The Waste Isolation Pilot Plant：A Potential Solution for the Disposal of Transuranic Waste
5	Risk and Decision About Disposition of Transuranic and High-Level Radioactive Waste
6	INDEPENDENT REVIEW OF THE SLUDGE SOLIDIFICATION WASTE TREATMENT PROCESS FOR THE TRU WASTE PROCESSING CENTER AT THE OAK RIDGE RESERVATION
7	Internal Dose Conversion Factors for Calculation of Dose to the Public
8	DOE National Low Level Waste/Mixed Low Level Waste Disposition Strategy