數位化技術
已為經濟高效的核電廠除役作業
做好準備

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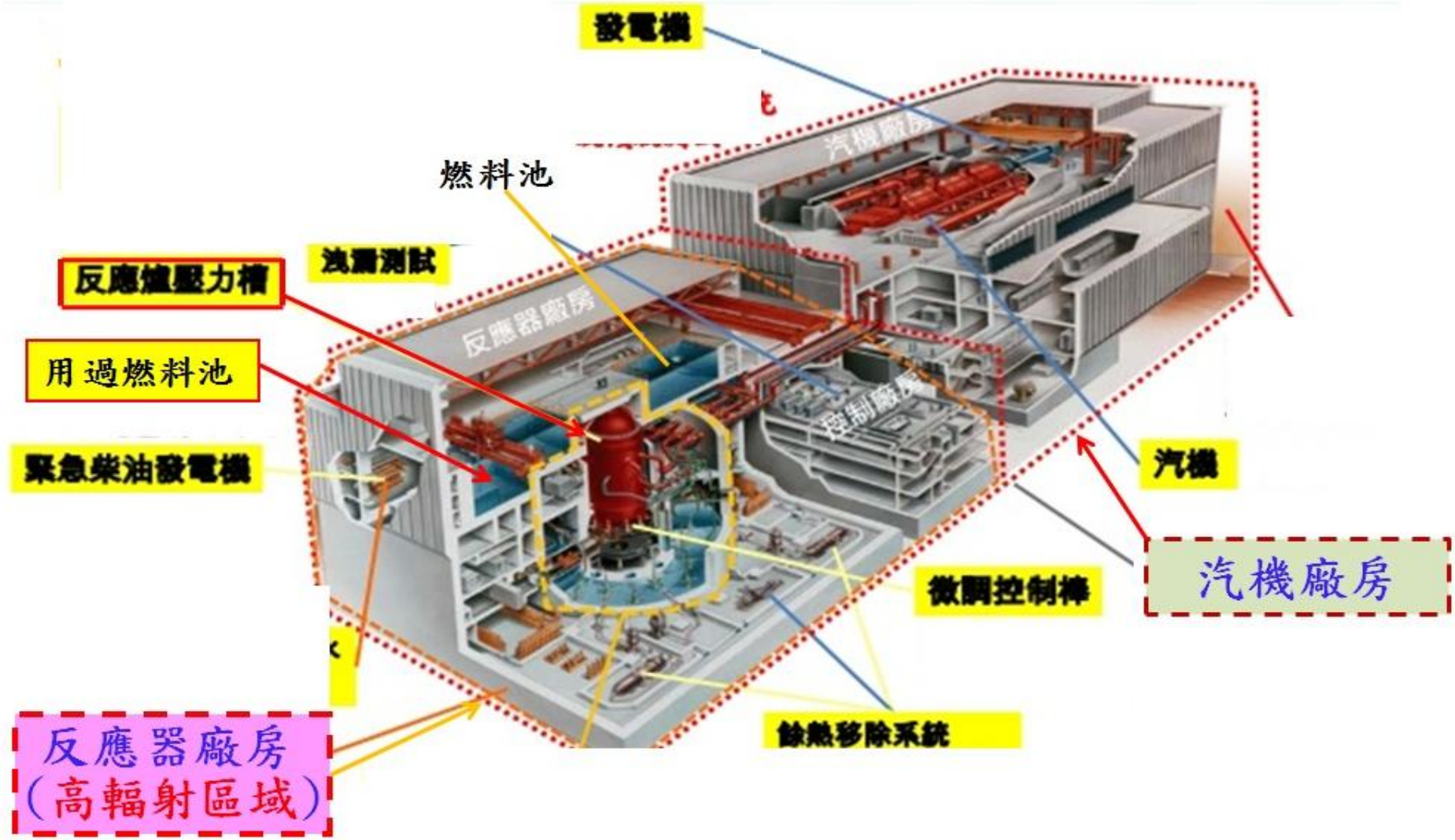
一. 前 言

數位化(Digitalization)技術在推動核除役專案方面發揮著重要作用，使專家能夠改進其規劃和執行。2021年8月國際原子能總署（IAEA）發布了<2021年核技術論壇>中,在涵蓋主題領域3內,對於除役項目指出:使用數位化、機器人和自動化技術的情況將會增加。接著, 2021.9.21.在國際原子能總署 第65屆大會舉行的一項活動中強調了3D建模和類比、可視化(Visualization)、虛擬實境(virtual reality)、人工智慧(artificial intelligence)、機器學習和其他類似應用在核除役規劃和實施中的實用價值。

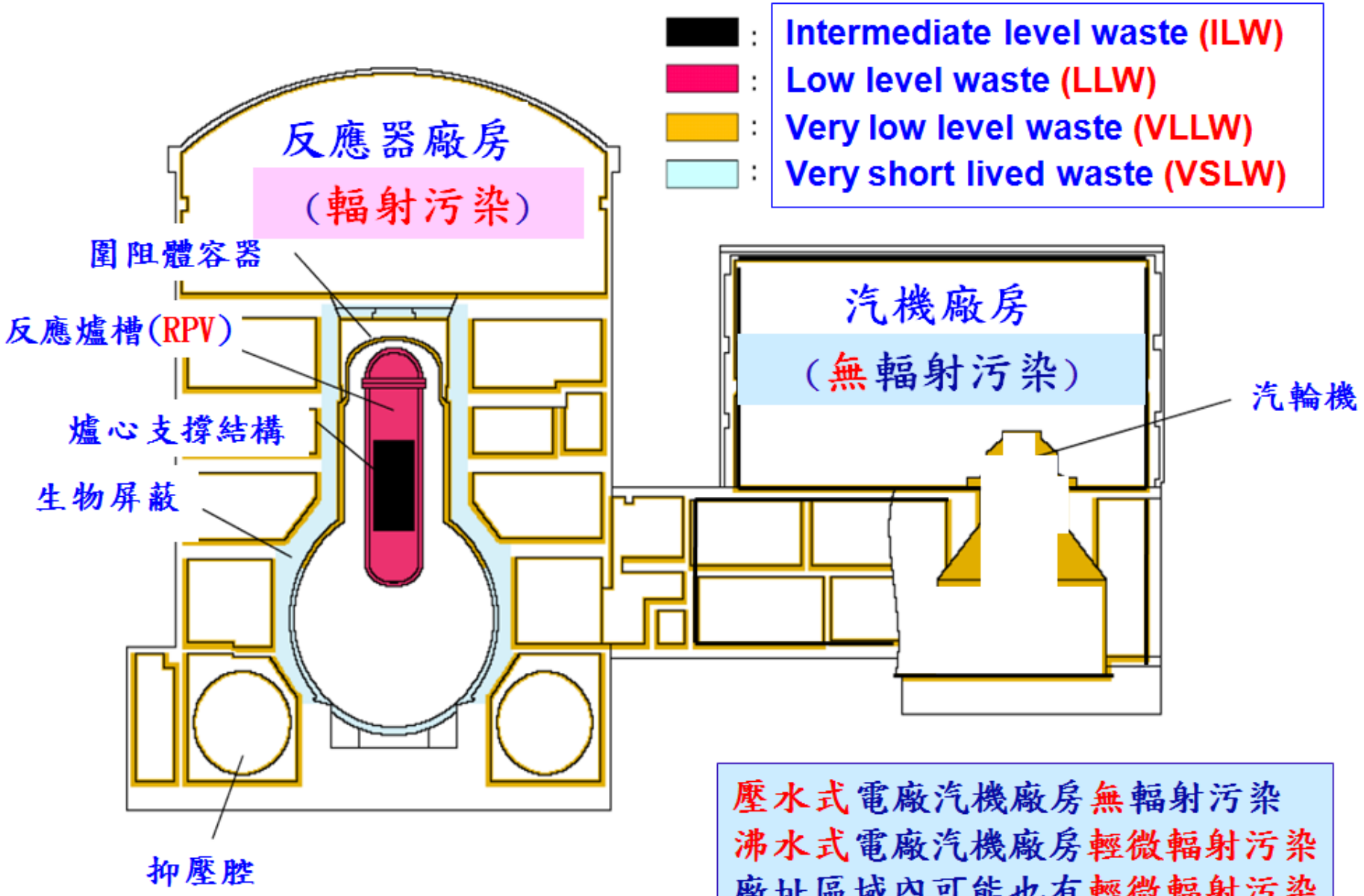
除役是一個多學科的過程，包括對廠區及其設施進行物理和放射性特性量測調查、對工廠和建築結構進行淨化和拆除等活動，最終使得該場地被重新用於其他目的。除役可能需要幾年到幾十年的時間，特別是在推遲拆除的情況下，專家預計數位技術將改進規劃並縮短完成這一複雜程序所需的時間。

國際原子能總署副總幹事兼核能部主任米哈伊爾·丘達科夫在會議中宣佈,為了繼續交流有關除役的資訊，原子能機構將於2023年5月在維也納主辦核除役問題國際會議：解決過去和確保未來。會議的目的是分享有關成就、挑戰和經驗教訓的資訊，以及能夠促進和加強安全、安全和具有成本效益的國家除役方案執行的戰略和方法的資訊。

壓水式核電廠(PWR)廠房剖面示意圖



廠房區域可能輻射污染特性範圍示意圖



壓水式電廠汽機廠房無輻射污染
沸水式電廠汽機廠房輕微輻射污染
廠址區域內可能也有輕微輻射污染

二. 典型核設施除役目標

除役計劃優質訴求目標應是：

1). 作業全程充分符合輻安及工安要求———————— 零傷害事故

2). 少量放射性廢棄物的產出————————佔拆除物料量的<6%

3). 使放射性廢棄物的產出及盛裝——符合最終處置接收條件

4). 拆除後無污染金屬、電氣及混凝土等物料——回收再利用

5). 使土地或設施可再利用————————(應含公共利益用途)

除役作業要求：

- 設施的輻射狀況評估
- 清除核設施的放射性物使廠址符合允許免管制水準及終止原許可證
- 證明該設施廢料滿足可免除管制釋放的要求

除役成功要素

安全、快速和具有成本效益：

- 有效範圍--優化的可能性
- 規劃/支源 + 數字映射(mappings)、數字類比,
  use of VR/AR
- 從廢料管理驅動除役作業 -- 從其特性掌握到免管制釋放
- 集成拆解-- 材料和廢料優化/管理
- 結合必要的核能程序使用工業常規技術和經驗
- 環境方面 -- 拆解、危險材料、回收利用
- 詳細的前期類比(simulations)-- 工具、程序、輻射、處理、運輸等等

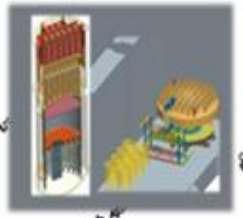
三. 世界進行中的核設施除役專案

Sellafield (UK)
Decommissioning Delivery Partner (DDP) (2016-26)

KKM (CH)
Fuel Channels Segmentation

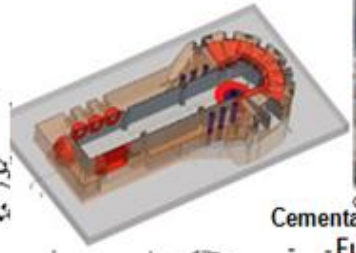
Barsebäck 1 & 2 (Sweden)
Reactor internals Segmentation (2015 -)

KKP 1 (Germany)
RVI and RV Segmentation and Packaging (2015 -)



GKNI (Germany)
RVI and RV Segmentation and Packaging (2015 -)

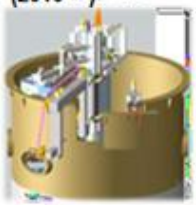
SVAFO (Sweden)
Bioshield demolition (2016 -)



101反應堆 (china)

Cementa
- Fu

EDF Chooz A (France)
RVI and RV Segmentation
(2010 -)



Grand Gulf (USA)
Steam Dryer segmentation (2012)

Fukushima Unit 3 (Japan)
Spent Fuel removal (2012 - 14)

Zorita (Spain) RVI and RV Segmentation and Packaging
(2011 - 15)

El Cabril Repository (Spain)
4-Year Operation and Engineering Support (2013-)

Interim Storage for Spent Fuel and High Level Waste (2013-)

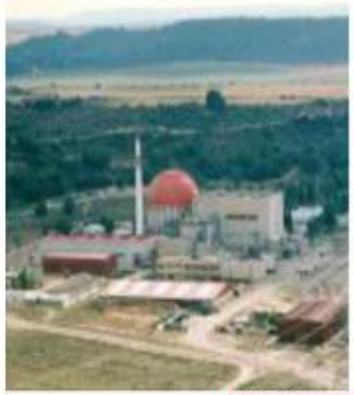
Decommissioning Studies (2010 - 14)

Kozloduy (Bulgaria)
LILW Repository Design (2012 - 15)

Decommissioning Plans:
- Bohunice, Slovakia (2013-14)
- Chinshan, Taiwan (2014-16)
- Kousheng, Taiwan (2016-18)

台電核一二廠

除役作業主要步驟



廠址特性調查

修建工程

拆卸

拆解

場址復原

系統設施輻射劑量和放射性廢棄物數量之直接量測估算

廢棄物料管理

核電廠除役放射性廢料類別/推估數量/成本

建築物/材料/組件根據設施污染定義放射性廢料的類別（藍色、黃色、紅色）和常規（白色）

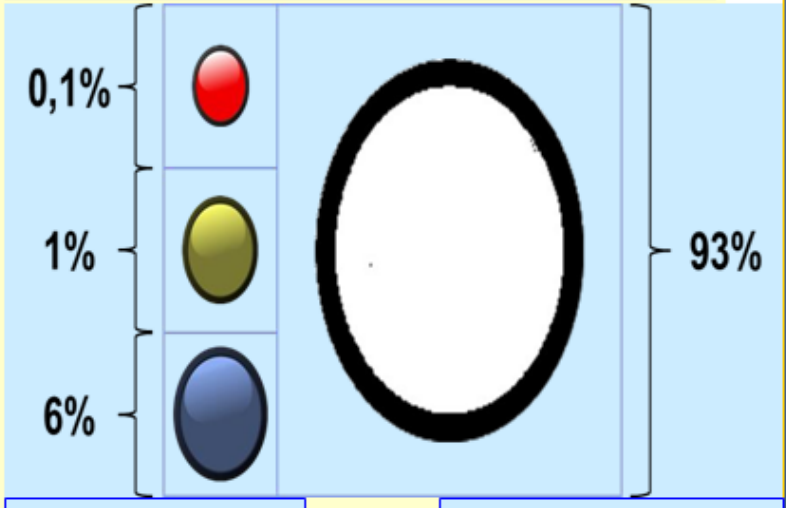
Red - Highly contaminated/activated
- Reactor Vessel and internals
- Primary Process Systems
- Biological Shield

Yellow - Medium contamination
- Process systems
- Buildings and structures
- Turbine and Turbine Systems (BWR)

Blue – Low contamination
- Buildings and structures
- BoP Systems
- Turbine and Turbine Systems (BWR)

White – Conventional handling
- Buildings and structures
- BoP Systems
- Turbine and Turbine Systems (PWR)

除役產生各類別廢料量比率



放射性廢料

清潔控解外釋回收利用

西屋公司推估:1. 瑞典每座NPP廠約 20 億瑞典克朗（不包括燃料和廢物最終處置）的除役成本,
2. 約7% 的放射廢物產生管理 > 70% 的成本！

四. 範例一. 數位化在廢址環境輻射劑量和放射性廢料數量調查的應用例

國際原子能機構(IAEA)的除役專家(Patrick O 'Sullivan)最近指出:

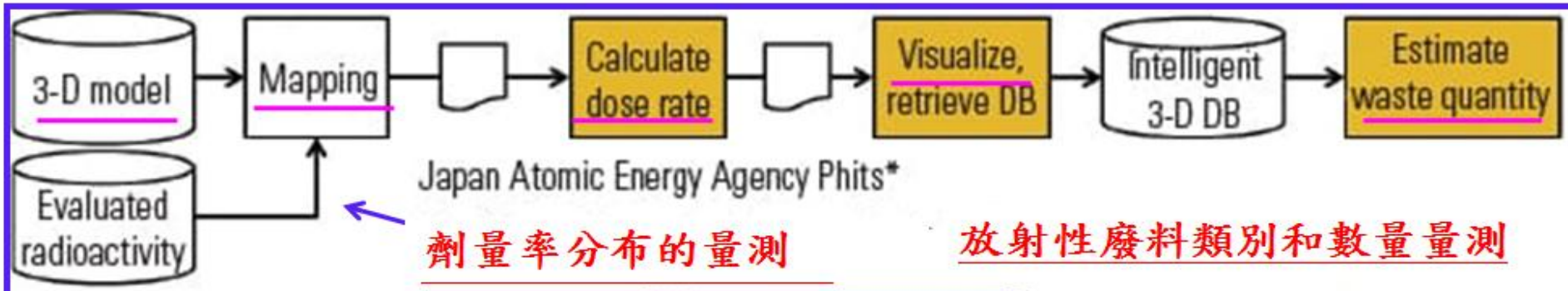
- 在制定除役計劃時,需要考慮的最重要事項是該設施的配置、物理狀況以及放性射污染的數量和分佈。詳細資訊可使用適當的特性測量程序進行優化
- O Sullivan提出該領域已獲得重要進展。其中3D輔助設計(CAD)、模式識別、無線通訊和雲端資料共享等技術正被用於改進 D&D 程序
- 準確計算必須作為放射性廢物管理的物料量基礎。具體地說,該系統工人的輻射劑量、工時數以及拆除產生的放射性廢料數量、拆除程序數據和殘餘放射性。
- 在虛擬環境中練習拆解活動是另一種方式,可以用來幫助盡量減少輻射暴露。他說,儘可能遠離輻射源的工人,這也可以減少受到的輻射劑量,只要可行,也可以使用機器人和遠端系統

簡而言之,利用3-D 模型和自動輻射劑量分布量測及VR工具為技術基礎可提供除役廠區場景及環境輻射視覺化(AR/VR)與輻射劑量和放射性廢料數量之資訊平台技能

先進的除役工程平臺,使用(3-D plant models),已可準確:

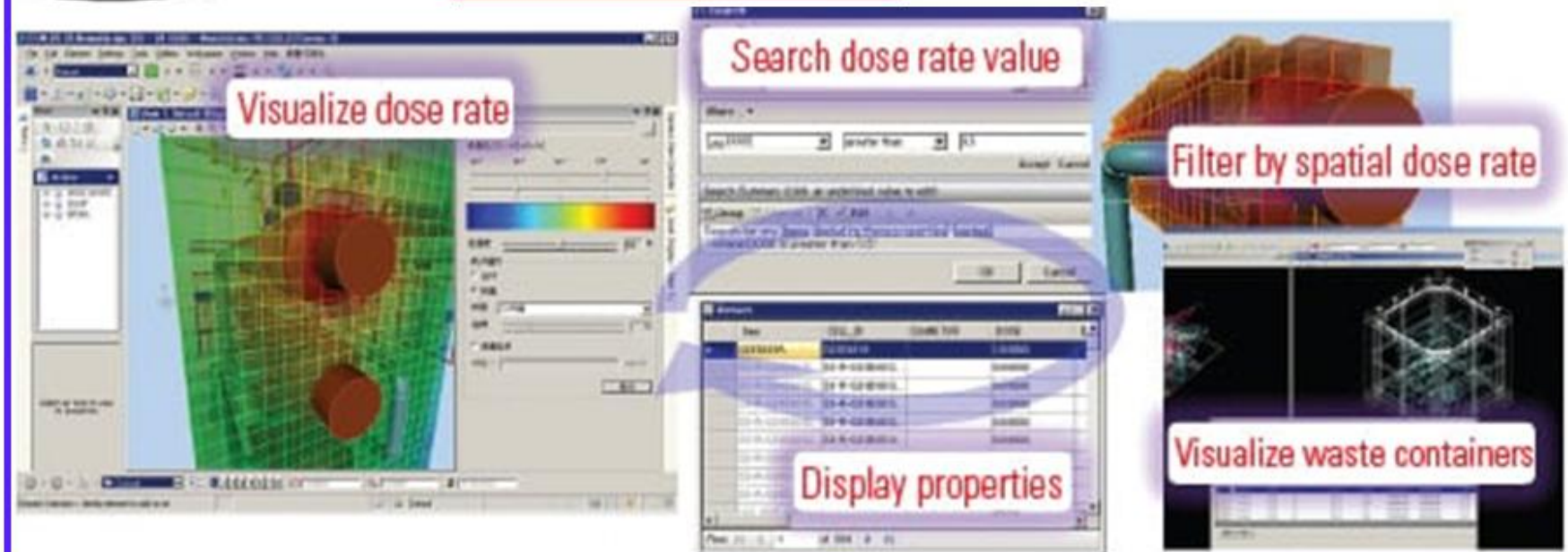
1. 評估現場拆除作業人員的輻射劑量和人力工時數
2. 計算作為放射性廢物管理的材料數量和拆除產生的放射性廢料數量、拆除程序資料。

利用已建立的 CAD 系統,結合輻射劑量率分布的mapping偵測 和定制的 MicroStation information modeling software資訊建模軟體和 i-model 技術, 以顯現基礎設施輻射和污染活度資訊



劑量率分布的量測

放射性廢料類別和數量量測



SYSTEMS, STRUCTURES AND COMPONENTS-- Advanced Services with iPIX Gamma Imager

FUNCTIONNAL CHARACTERISTICS

- Real-time portable Gamma-ray imaging system
- Mask #2 yellow (rank 7 / 4 mm thick) for medium-low energies and background < 10µSv/h
- 2 m (6 ft) and 10 m (32 ft) Ethernet cables
- Software
- Fully rugged convertible notebook
- Manual Tripod
- Dedicated transport case
- POE injector
- USB key
- Bumpers and handle
- User Manual
- Power cables

CANBERRA

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MIRION TECHNOLOGIES

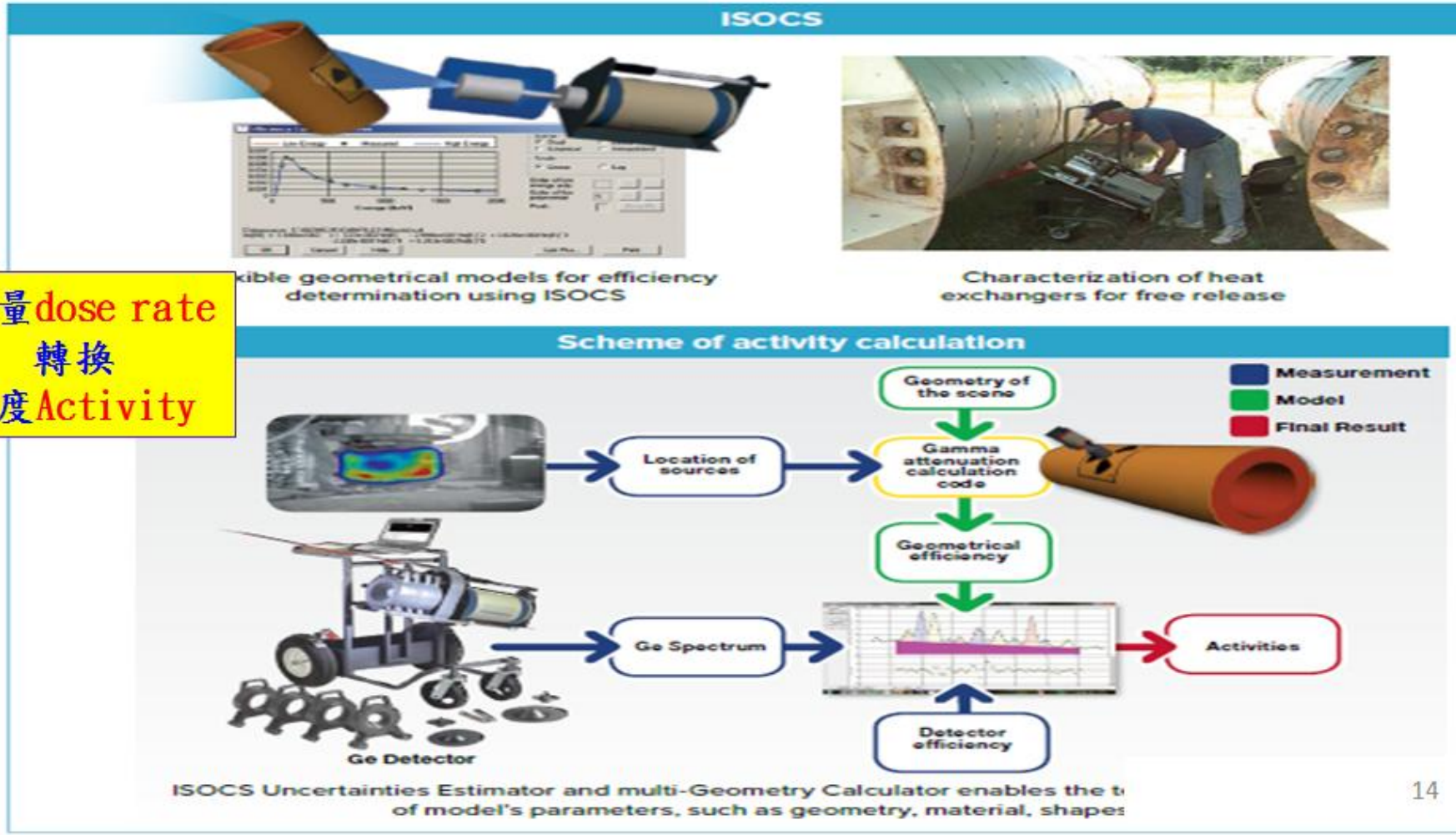
SYSTEMS, STRUCTURES AND COMPONENTS

使用下列方法可以描述預計拆除廢料部件,如管線、管道、通風系統和小不規則物體的污染情況。

ISOCS 是評估這些預計拆除廢料持續儲存或處置廢物活動的優良工具。

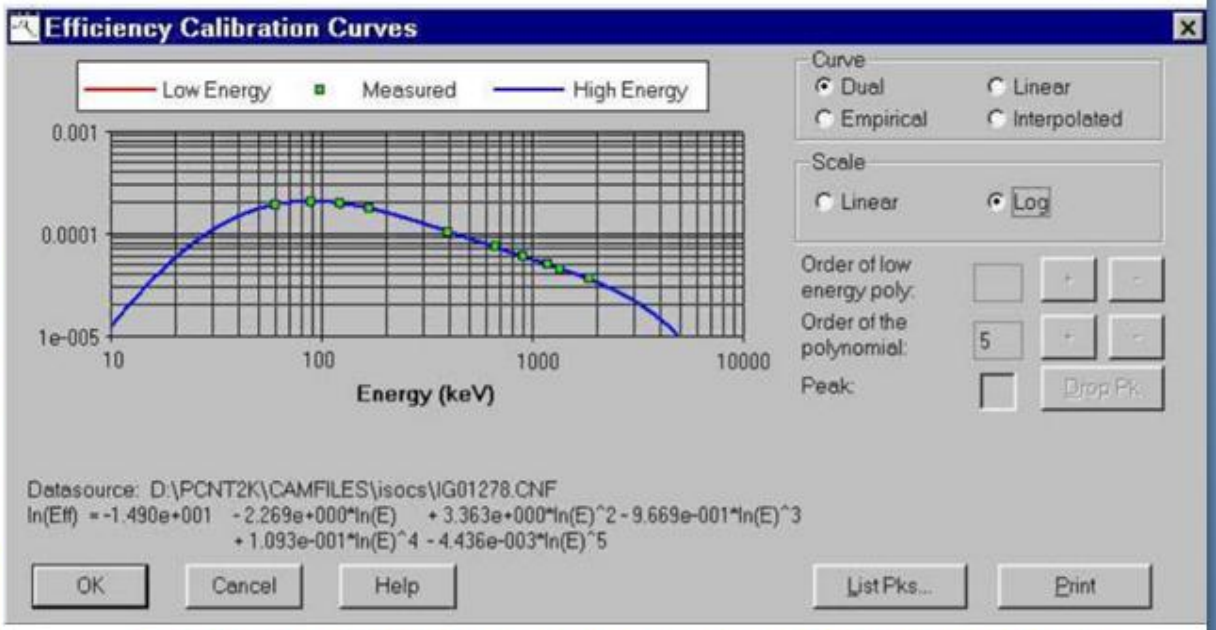
ISOCS 可以與 iPIX 伽馬成像儀一起部署，以便即時定位熱點。

劑量dose rate
轉換
活度Activity



ISOCS is an excellent tool to evaluate the activity of these components for continued waste storage or disposal

ISOCS cart with detector, cryostat and modular shield system



ISOCS efficiency response curve interface

Activity measurement: Method

- Locate the contaminated source (using gamma imaging system and/or Geiger Mueller detectors).
- Use spectrometer (HPGe, CZT, NaI or LaBr, etc.) to obtain gamma spectrum of the hot spot(s).
- Use an ISOCS template to obtain the geometry detection efficiency (Gamma attenuation calculation code).
- The gamma spectrum will be analyzed using spectroscopy code (Genie™ 2000 software), combining the detection efficiency from the ISOCS template and eventually deducing the activities of the contamination / source(s).
- Advanced In-situ Gamma Spectrometry (AIGS) Services can greatly improve the accuracy of activity results based from the

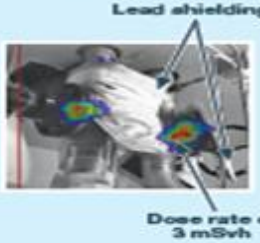
iPIX Gamma Imager: Real-time Monitoring & Hot Spots Localization

iPIX is a unique gamma imager that quickly locates low level radioactive sources from a distance while estimating the dose rate at the measurement point in real time. It is the ideal tool to map a radioactive area before entering the zone, thus reducing the dose exposure (ALARA) for the workers.

Due to the use of the coded masks, the need for heavy shielding has been eliminated, making it a compact and lightweight (~2.5 kg) system.

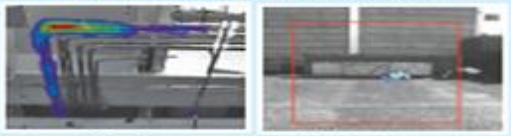
- iPIX is an excellent tool to precisely locate the radioactive source position. Knowing the position helps to improve the activity calculation correctly when using the ISOCS system.
  - Best tool to track low energy emitters.
  - Industrial design for use in harsh environments (IP65).
  - Can be operated remotely minimizing exposure to the operators (ALARA).
  - User friendly, with push button image acquisition.
  - High performance to quickly and precisely locate hot spots.
  - Estimates dose rate at the measurement point.

iPIX allows localization of radioactive sources in many kind of nuclear plant components, building, pipes, drums, scraps, etc...



Lightweight unit can be deployed and transported in the field

NPP Example – Setup and Control of Radiobiological Protection

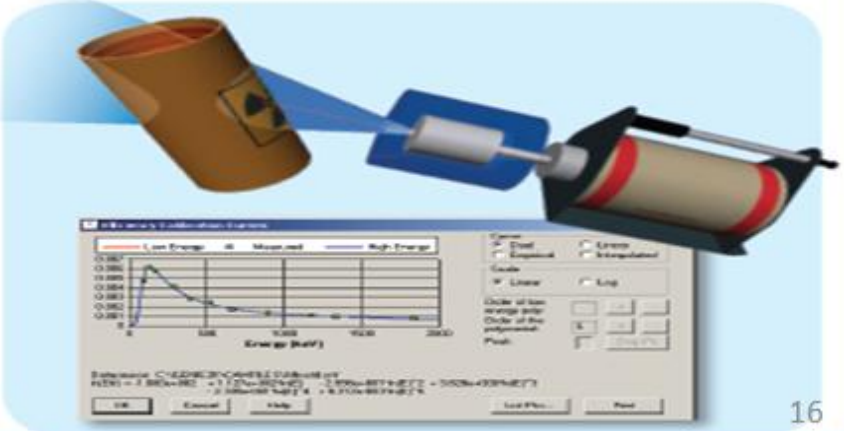


ISOCS System Measurement

- The In Situ Object Counting Systems (ISOCS) is commonly used to measure contaminated materials and areas, both in place or after removal from the facilities, also for final status measurement to the clearance.
- HPGe detectors have the best FWHM resolution in gamma spectroscopy and allow fastest specific nuclide identification, even with complex spectra. NaI detectors have a good efficiency for very low activity determination of simple nuclide mixes. CZT detectors are small but have a better energy resolution than NaI detectors.

Key benefits

- Immediate, accurate, nuclide-specific results for in-situ measurements of any object or surface.
- Source-Less detector-specific calibrations generated by software as the sample is being calibrated.
- All calibrated objects/surface are usually plane, cylinder, box, sphere, well/Marinelli or pipe.
- Mobile detector positioning device includes 25 mm, 50 mm collimators (for HPGe detectors) and backshields. It accommodates any detector orientation. Custom-designed collimators can also be used.
- Complex pipe template allows modeling of complex, multi-layer pipes and drums.
- Allows modeling of In depth profile contamination.
- Wide range of detectors (HPGe, NaI, CZT, LaBr) compatible, allowing operation for range of applications and activities.
- Use of Advanced In-situ Gamma Spectrometry (AIGS) Services to optimize waste segregation by improving assay accuracy (for example when activity is inhomogeneous).



Dose rate measurement + mapping

Mirion offers dose rate meters for a wide range of users and probes to suit many applications.

All CANBERRA™ Smart Probes can be plugged to the Mirion family of Smart survey meters. A GPS survey meter is available to identify the position of measurements and give a real time measurement of dose rate and gamma spectra simultaneously.

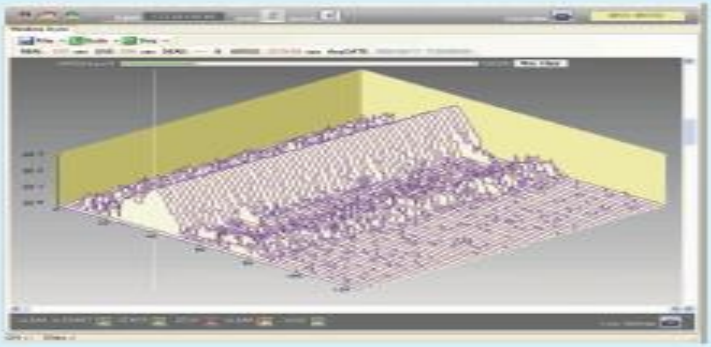
A COLIBRI Communication ALARA Platform

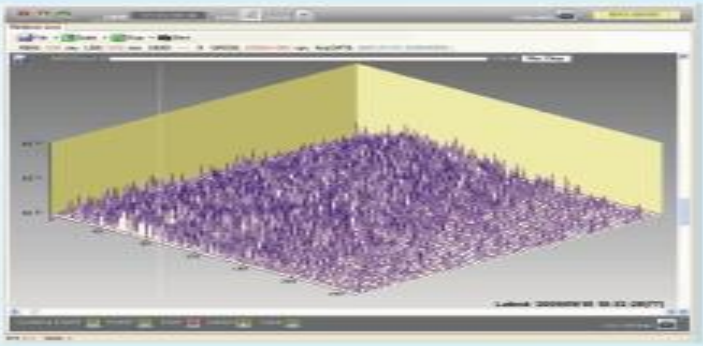
LynxNavi is a software developed for supporting all acquisition modes proposed by the Mirion high performance multi-channel analyzers (MCA) using NaI to obtain gamma spectra and with high performance analysis.

LynxNavi used with the Osprey® MCA

Uses our unique "Time-to-Count" technique with many of its Geiger Mueller detectors

Many Mirion detectors are appropriate for different levels of dose rate measurement, giving 3D mapping of dose rate and gamma energy on a large surface. The Colibri instrument is equipped with a GPS system, giving an accurate mapping of a large surface.



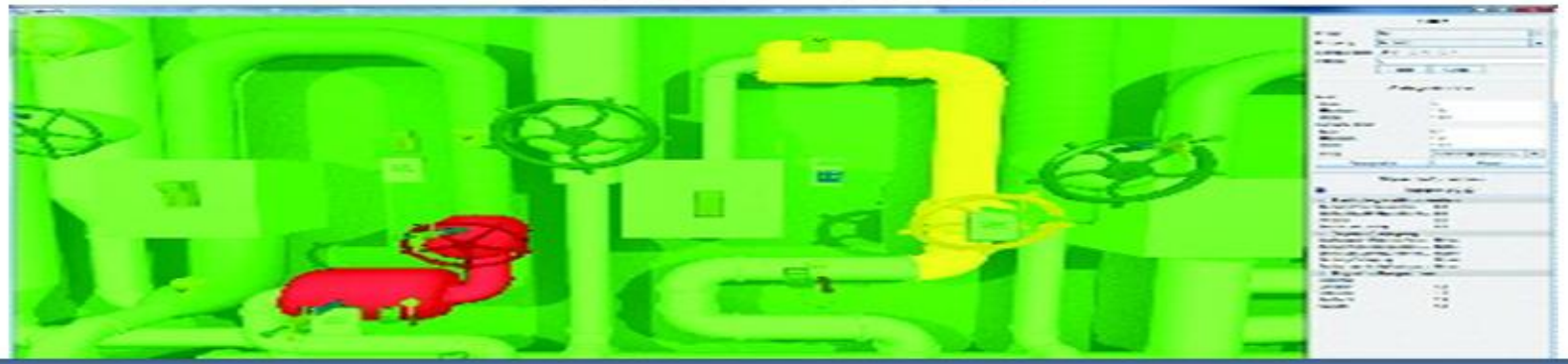


VR視覺化情形

上圖資料，是基載於3D 模型介面顯示設施系統組件的環境特性資料

下圖顯示這種VR視覺化介面如何配備有效的輻射特徵功能

互動式 3D 使用者介面概念，可充分應用於管理除役資料庫（右面上表）、視覺化污染、結構和廢棄物分類以及放射性廢物量化（右面下表）



下圖 1 和圖2 中，分別為日本Fugen NPS 和 Halden 沸水反應器的VR視覺化輻射條件案例。使用者配置顏色刻度和振幅，以指示輻射水準

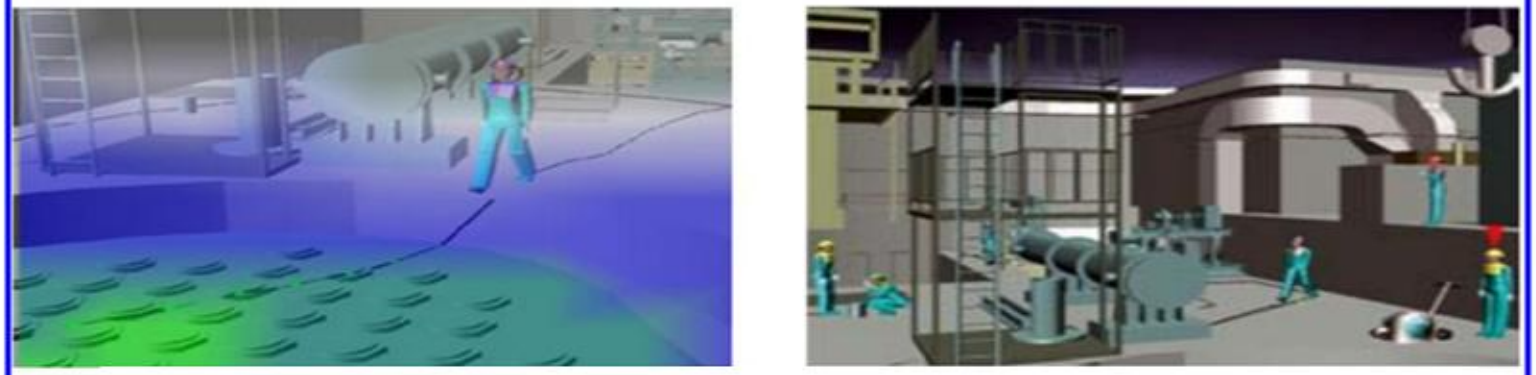
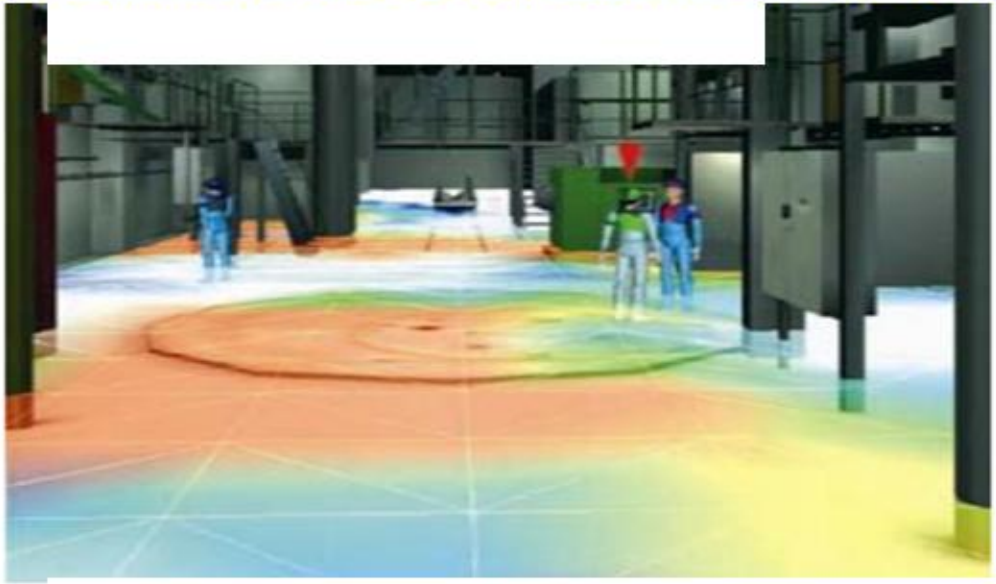


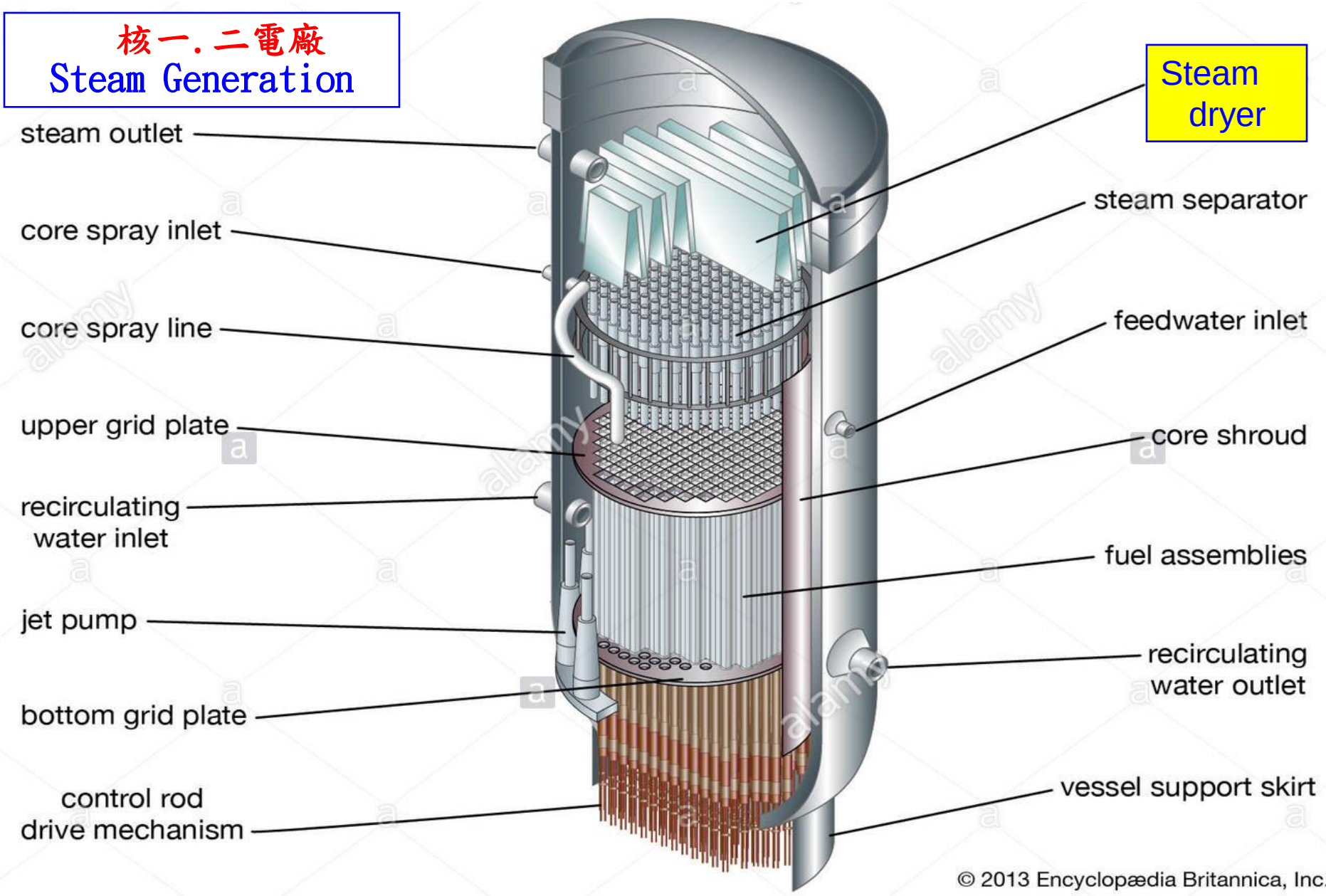
Fig. Radiation and work visualization at Fugen NPS



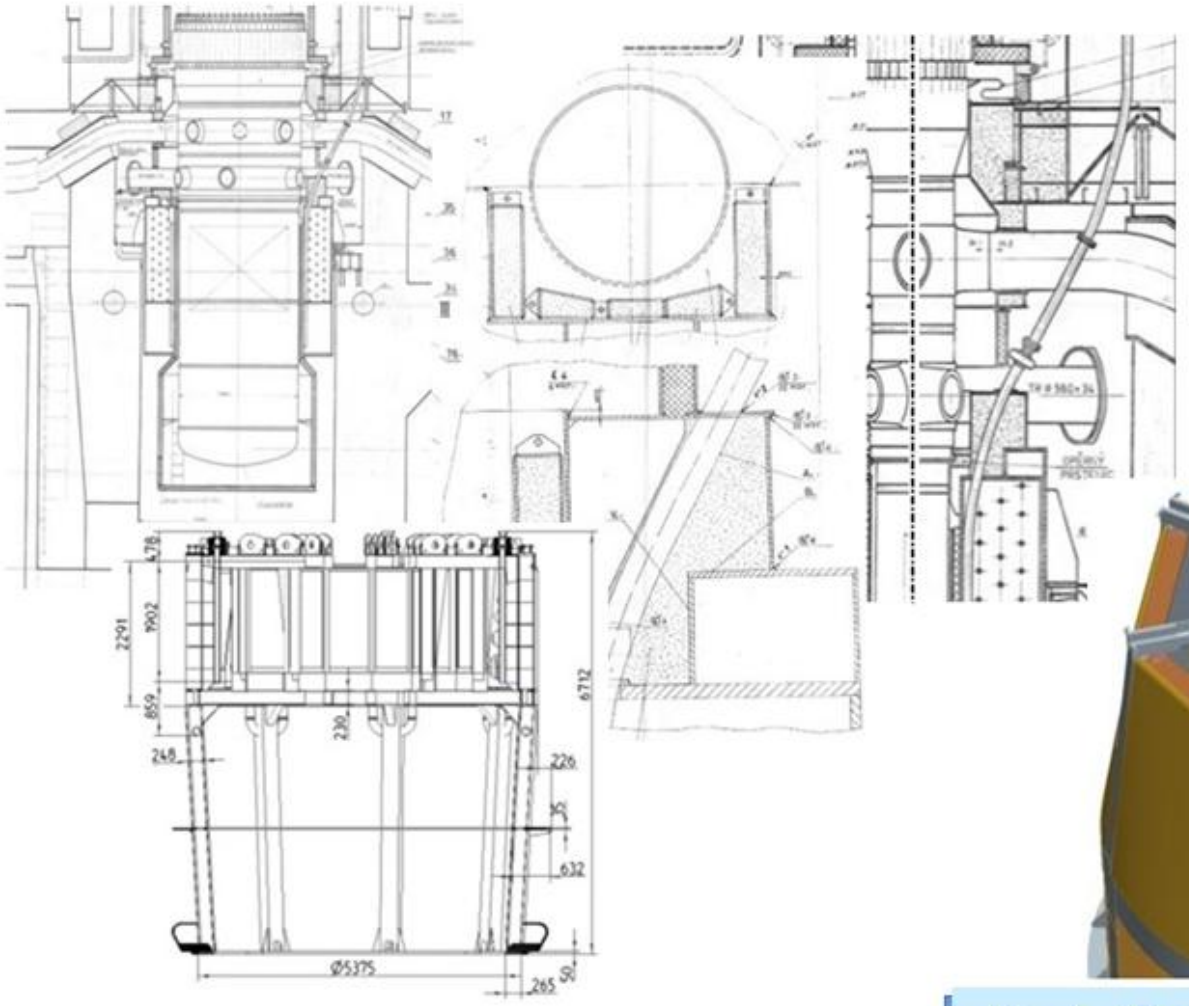
Test work scenario in the Halden Reactor

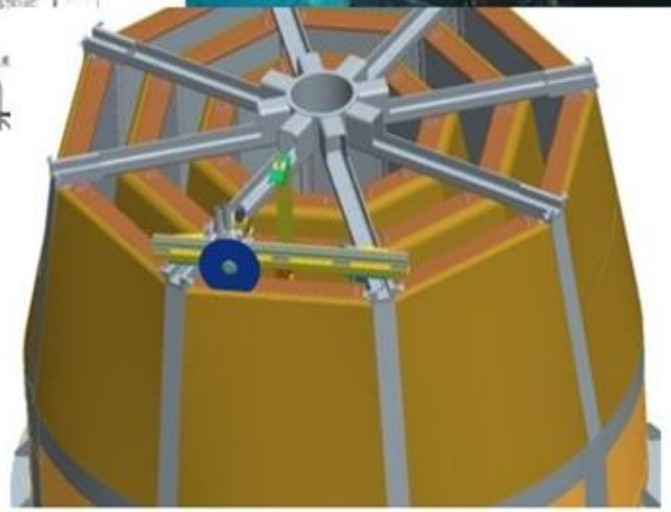
五.範例二/1. 數位化-- CAD應用在蒸汽乾燥器的拆解

核一.二電廠
Steam Generation



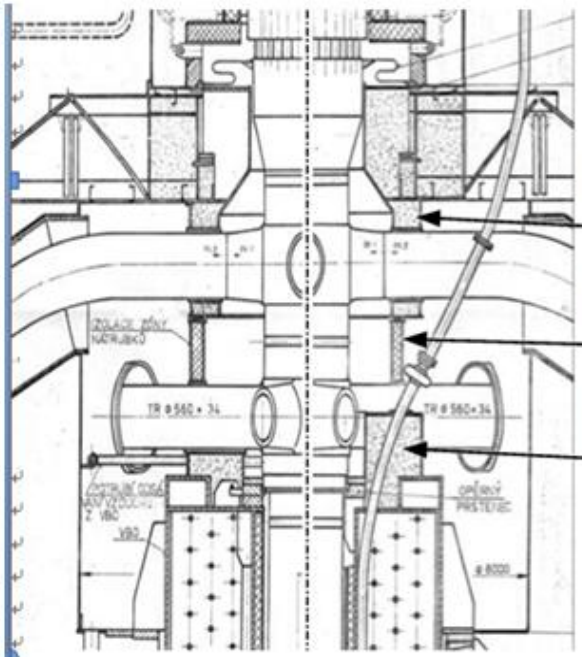
五. 範例二/2. 數位化 - 3D CAD 模型的繪製

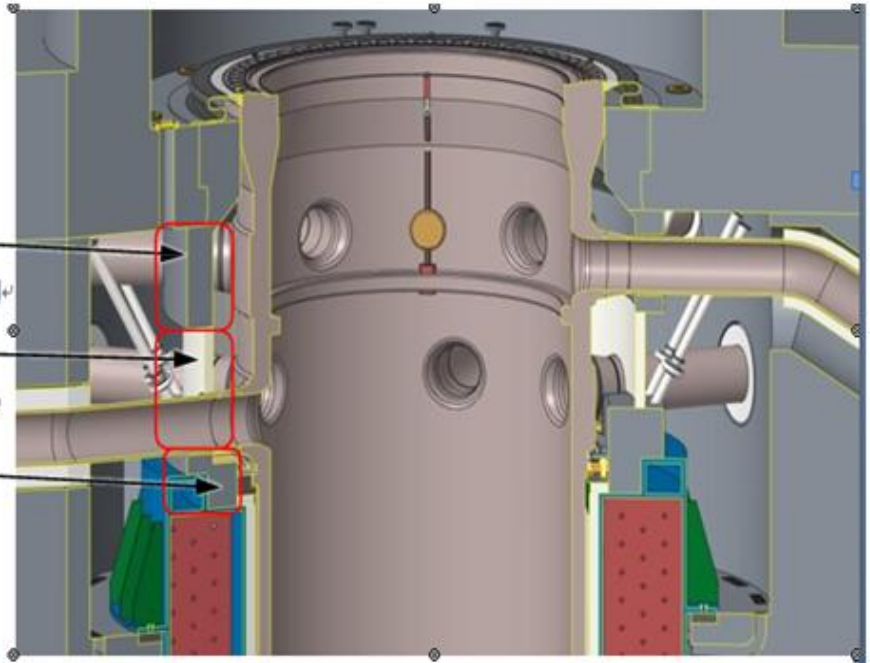


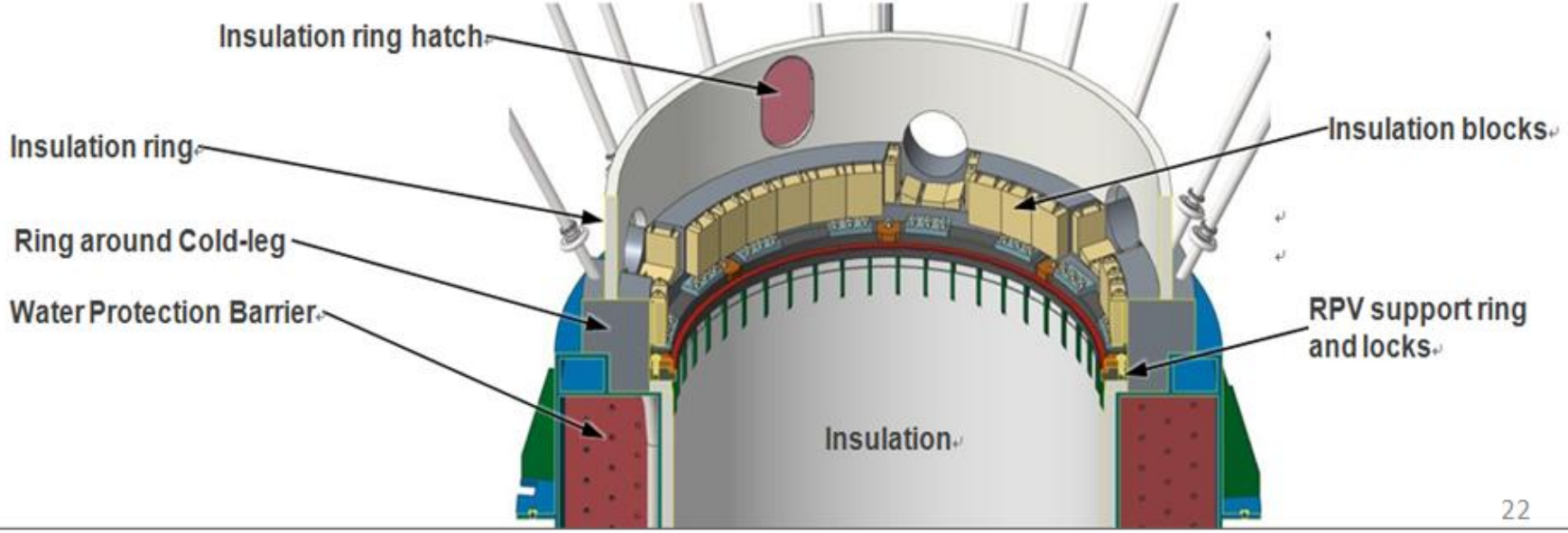


所有作業工具、配件裝置和
程序的前期類比/驗證

五. 範例二/3. 數位化- 3D CAD模型的RPV支撐環切割規劃



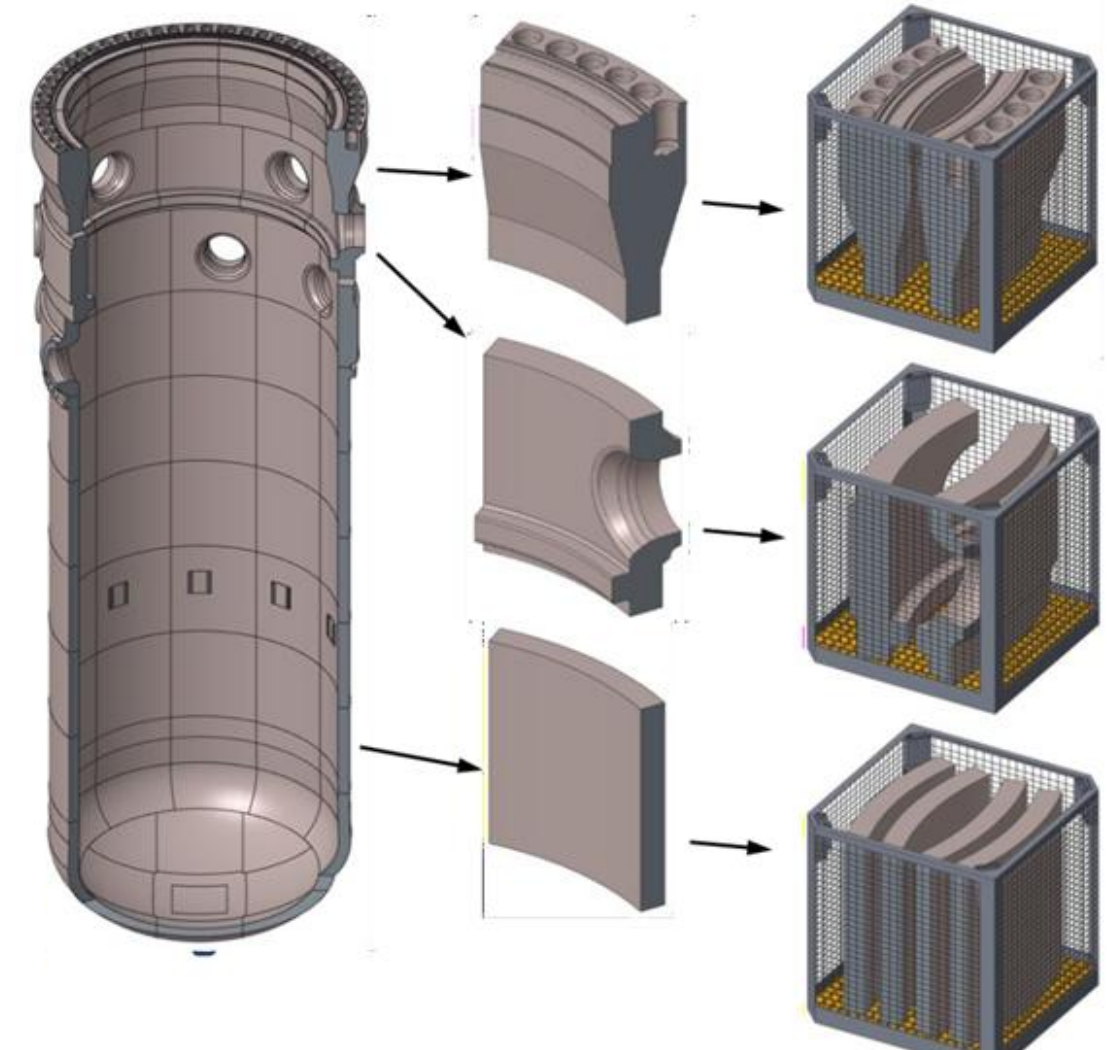


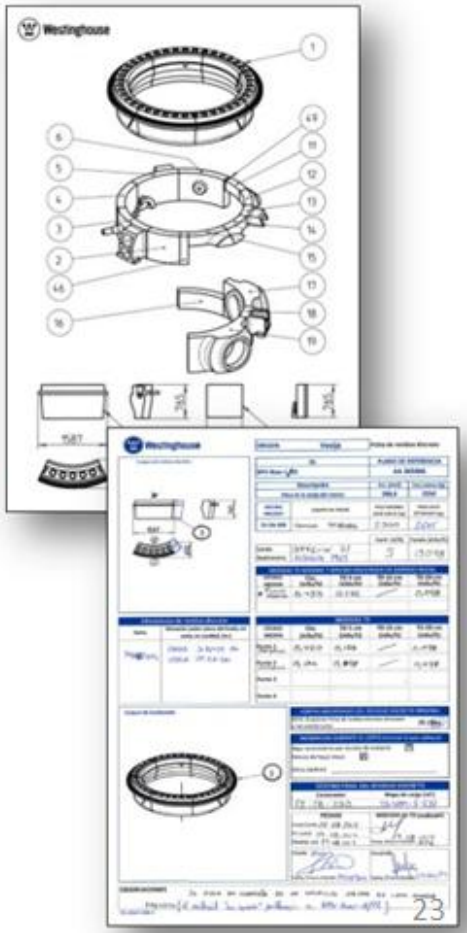


五. 範例二/4. 3D CAD 模型的RPV切割和包裝--前期準備

優化切割和包裝，包括劑量計算和文件檔案

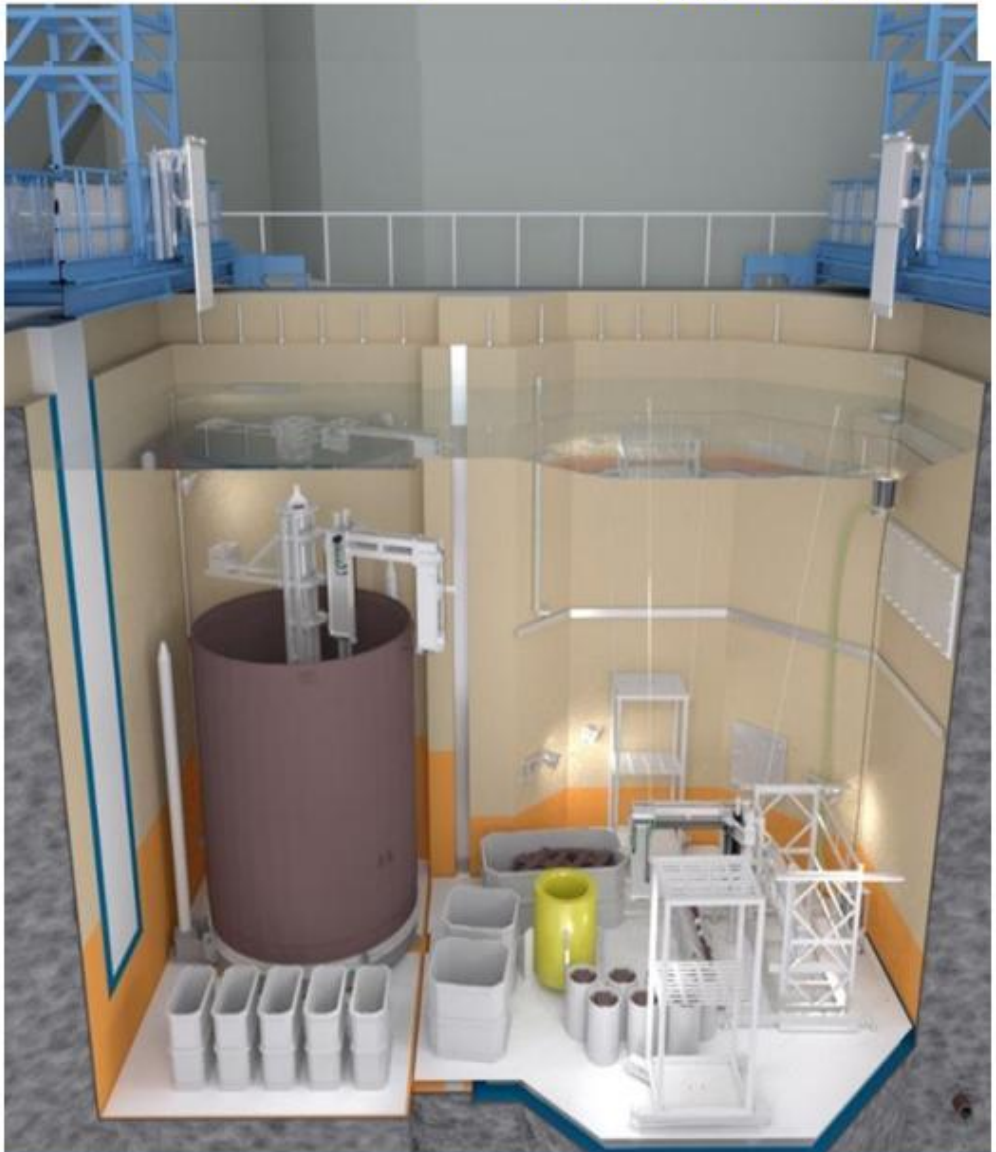
拆除廢料不同活度類別,須前置裝入不同規格提籃

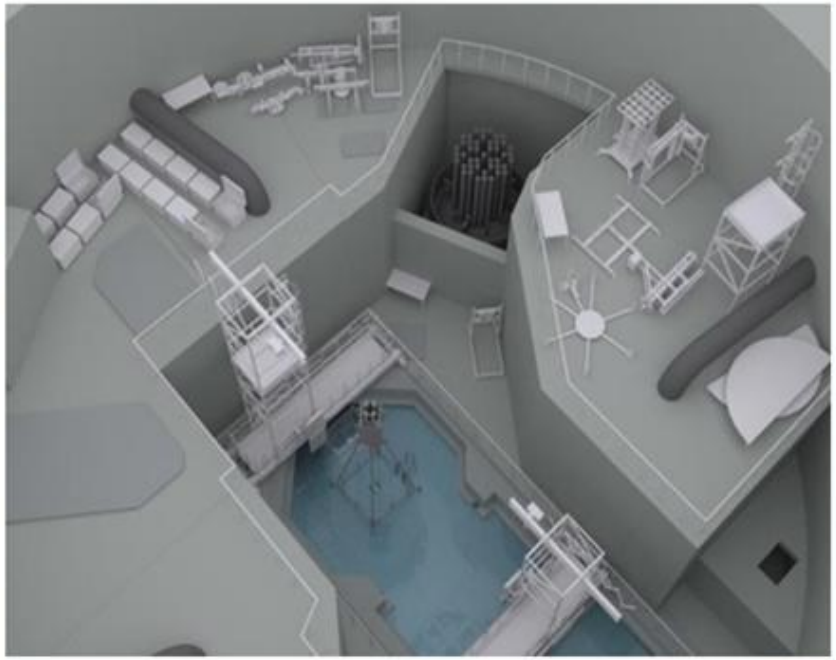


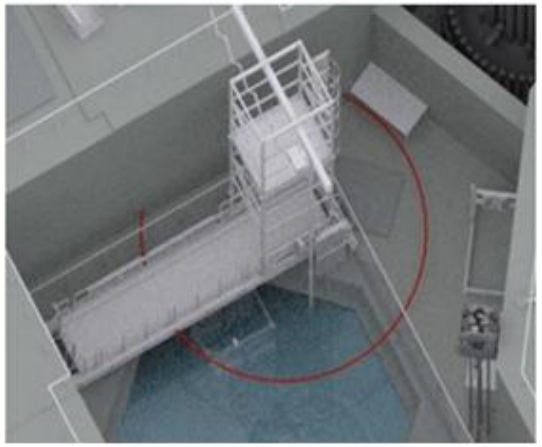


五. 範例二/5. 3D CAD 模型的RPV切割和包裝序列/佈局和存儲規劃

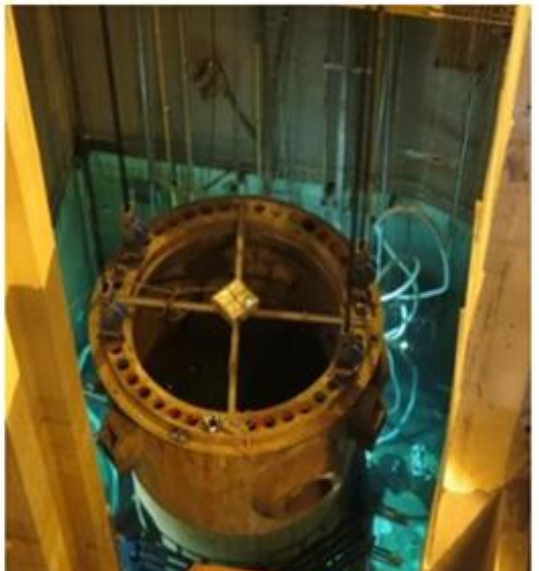
In CAD systems, VR 作為技術輔助







五.範例二/6. 提升 RPV 和 CAD 模擬和Laser掃描



五. 範例二/7. 廠內組件的點雲(Point Cloud)解決規劃

Real Plant 3D

3D-Scanning	3D- Foto	3D- CAD	Gamma scanning



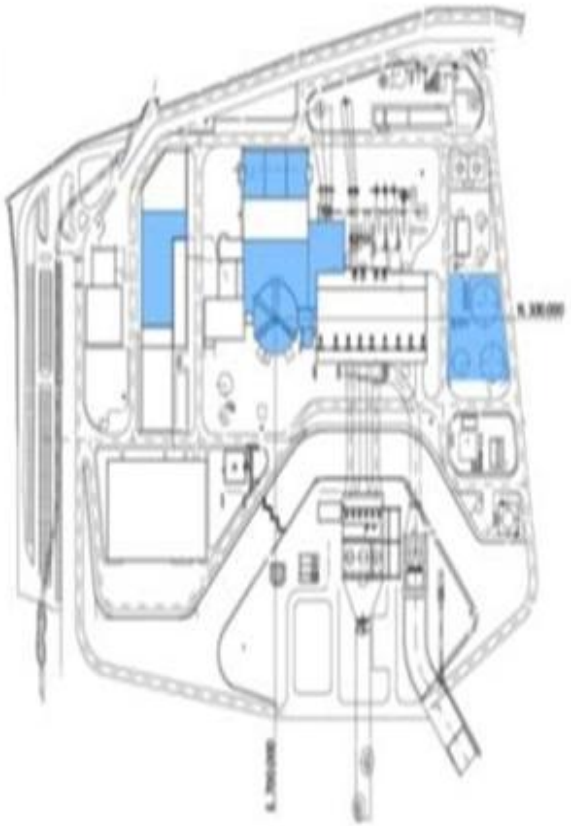
VR Virtual Reality


Several commercial products available

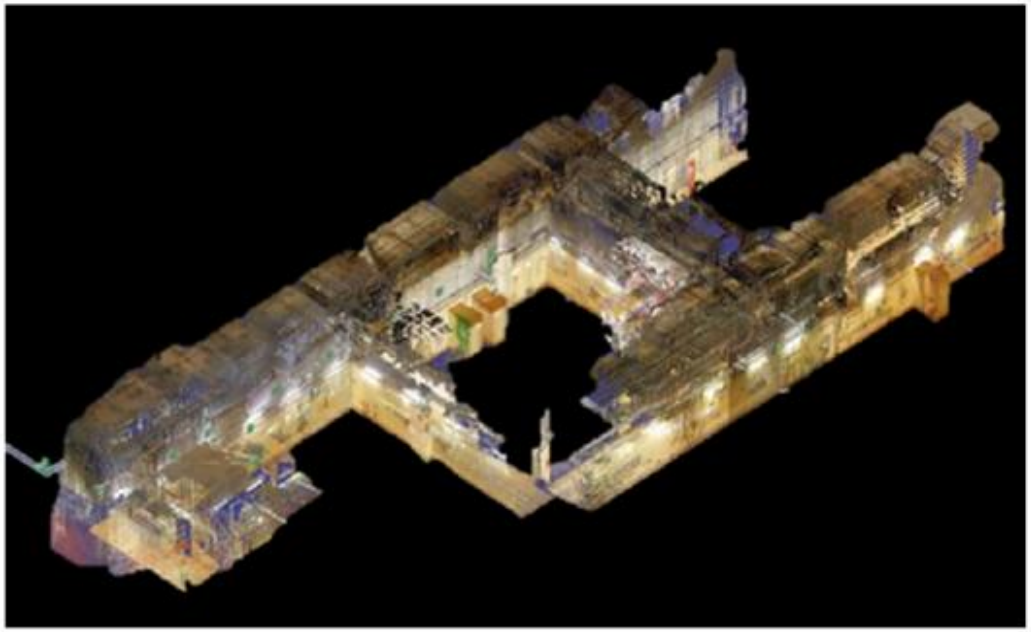
- Laser scanning/high-resolution photos
- filming
- Photogrammetry
- -3600 VR/AR

AR Augmented Reality


五. 範例二/8. 建築物和房間的點雲解決方案



ic

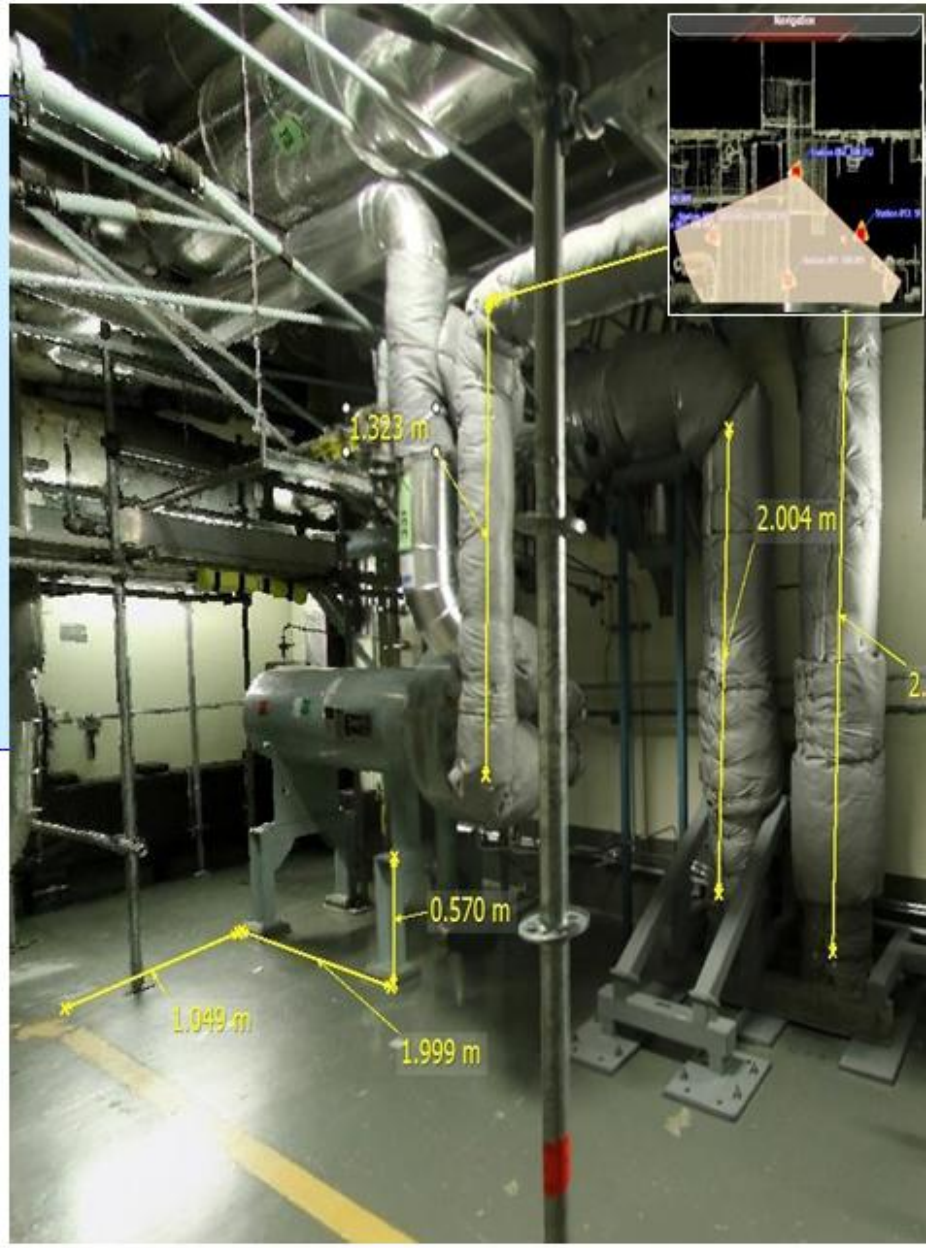


From plant layout to specific buildings and rooms

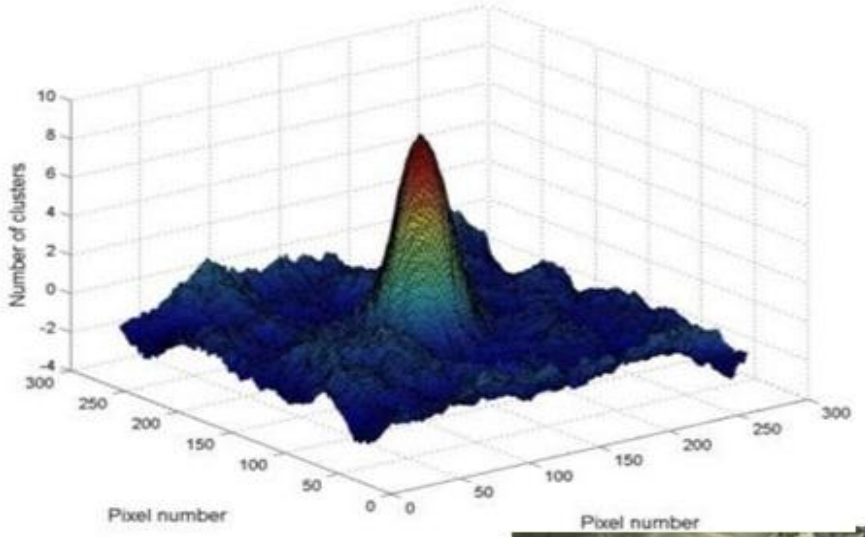
五. 範例二/8. 建築物和房間的點雲解決方案(續)

Laser scanning and high resolution 3D Photo:

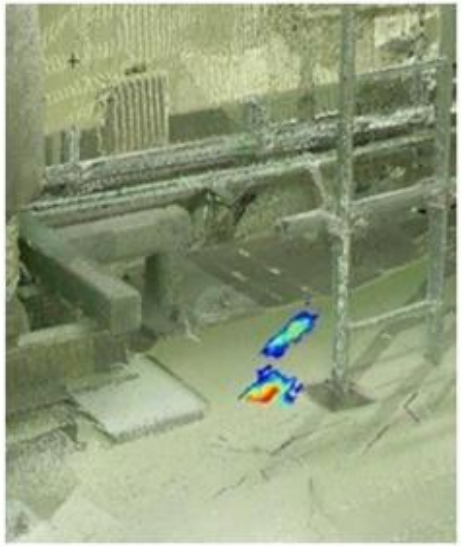
- Google Street view
- Measurement directly in the picture
- In-build navigation tool
- Possible to add dose information



五. 範例二/9. 點雲解決方案-伽瑪掃描(Gamma scanning)



Multile gamma camera 2D pictures are transformed to 3D and incorporated into the cloud points

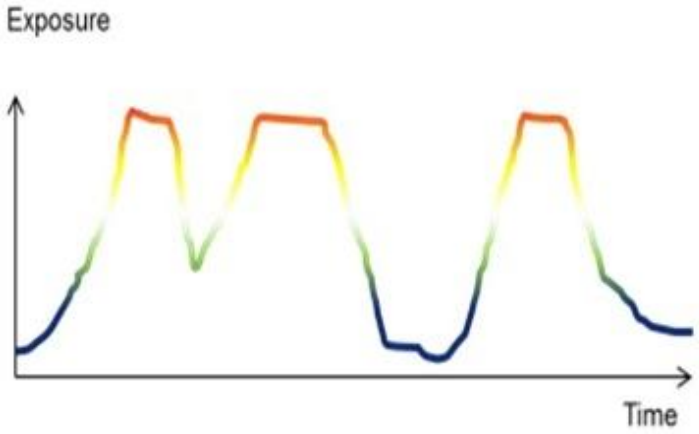


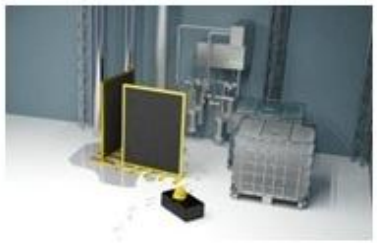
五. 範例二/10. 輻射類比和VR應用

劑量率類比是採用伽馬測量

不同系統組件拆除分離
以不同廢物類別路線管理

輻射類比 (exposure, shielding, procedures, training)





結　語

- 除役數字化已成為:安全、快速和具有成本效益的重要先進技能
- 市場上已有幾種經驗反饋
- 數字化核電廠資訊使前期模擬能夠優化進度、技術和成本
  - 核電廠主要組件如RPV、RPI 等，經由 CAD圖文可進行數字化
  - 廠房建築物和設施，利用點雲技術解決方案可進行數字化
  - 劑量率和廢料量及類別資訊和調查測量也有成功解決方案