Transport of Radioactive Materials

放射性物質的運輸

王鴻椿* 李蓬 吳建興*****

編者按:

在前輩王鴻椿船長的主持下，本著希望對會員介紹有輻射劑量的貨物運送，提供相關文件參考．然而一則是本議題的資料常常需要更新，二則是原本的文件需要授權．因此在網站上取得上述資料翻譯後做一先遣報告，再加上王船長的資料完成此文．此文雖說有針對鐵路或公路運送部分，其實在航業的整體運輸上是大同小異的，甚至於是相互包容的．希望能滿足船長們對知識的需求．如果在翻譯上或知識更新上有疑問者，請不吝提出指教．

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* 王鴻椿船長 船員公會理事

** 李蓬船長 船長公會秘書長

*** 吳建興船長 建華海運船長

1. 一般將具有輻射性貨種/櫃種分成四類:

甲、UF6/UF6 貨櫃

六氟化鈾是一種鈾的化合物，其化學式為 UF_6。六氟化鈾被用於製取濃縮鈾，因此在核工業中有很重要的價值。標準狀況下，六氟化鈾為灰色的晶體。六氟化鈾有很強的毒性，可與水劇烈反應，並且能腐蝕大多數金屬。它與鋁反應溫和，因為鋁的表面在空氣中會形成緻密的 AlF_3 薄膜，阻止進一步的反應。

製作方法是磨碎鈾礦（U_3O_8，或稱「黃餅」)，並將其溶於硝酸，產生硝酸鈾酰 $UO_2(NO_3)_2$ 溶液。萃取純化後，使硝酸鈾酰與氨反應，生成重鈾酸銨 $(NH_4)_2U_2O_7$。加氫還原得到二氧化鈾，再與氫氟酸反應生成四氟化鈾。四氟化鈾與氟進行氧化反應產生 UF_6。

黃餅(yellowcake)是從瀝青鈾礦中提取高純度鈾的中間產品，外形一般為黃色粉末，不溶於水，味道刺鼻。具體成分根據鈾礦的品質和提取過程不同而各異，主要成分是鈾的氧化物，常見含量約 80%，熔點約 2878°C。

UF6 之所以那麼重要是因為各種主要的鈾濃縮方法，不論是氣體擴散法，還是氣體離心法都需要用到它。

UF6 一般儲存於氣體鋼瓶內。

48G Depleted UF_6 Storage Cylinder

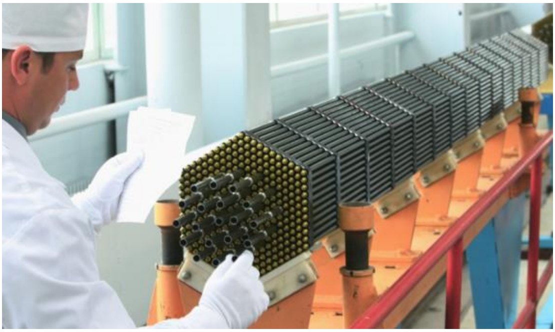
After enrichment, depleted uranium hexafluoride is placed in large steel cylinders for storage.
The most common storage cylinders have a 48 inch diameter.

乙、UO2 粉狀物/UO2 粉狀物貨櫃

UO2 常溫正常壓力下為深褐色的粉狀物, 不容易自燃或燃燒, 亦不會有自然化學反應, 亦不輕易溶於水或爆炸. 一般裝於有隔熱材的包裝內, 隔熱材的厚度視材料而定.

丙、核燃料組件/燃料棒專用櫃

核燃料組件基本上是以棒的形態出現

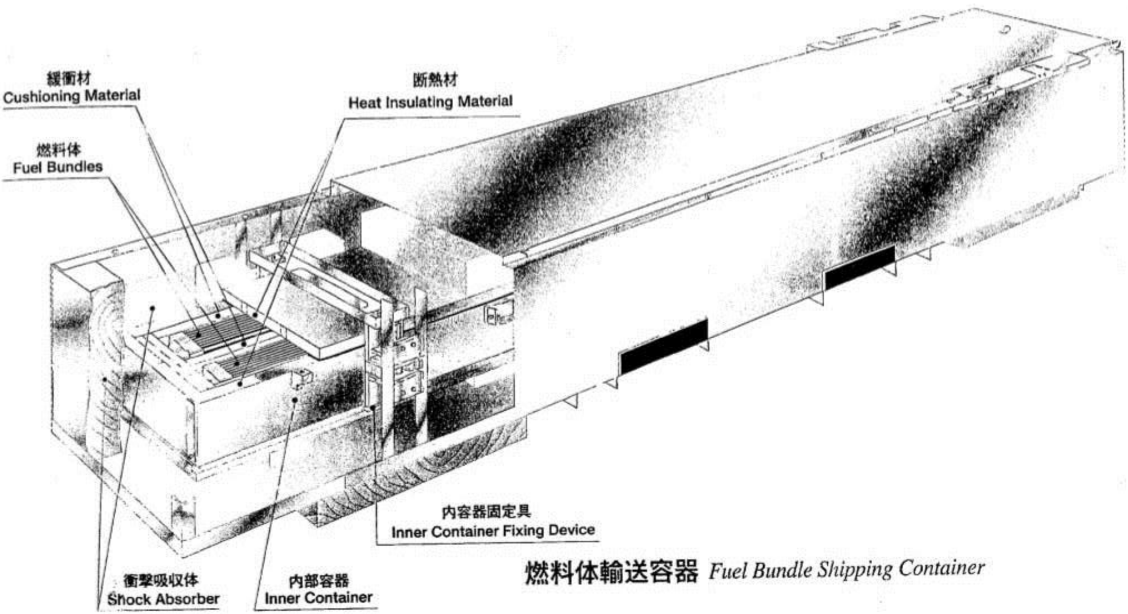


丁、曾裝運輻射貨物的包裝物(含櫃本身):

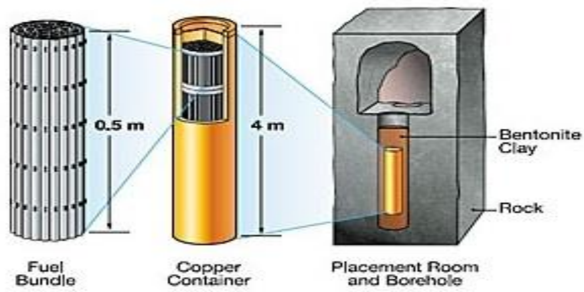
基本上是以普通貨物來做承運, 然而卻必須存放於一般貨櫃中. 如果其輻射大於以下數字, 才考慮以輻射貨品運送.

- 自然的 UF6 0.7% U-235
- 濃縮的 UF6 4.9% U-235
- UO2 粉末 3.0% - 4.9% U-235

裝載輻射品需要有兩層的包裝, 因為它必須要隔熱與防震



燃料体輸送容器 *Fuel Bundle Shipping Container*



2.輻射物在水裡對環境的影響程度

品名	在水裡的表現	對環境的影響
自然 UF6	慢慢溶解及擴散	無影響
濃縮 UF6	慢慢溶解及擴散	無影響
UO2 粉末	只會溶解 0.9%,慢慢擴散	無影響
燃料棒	逐漸淋溶及擴散	無影響

3.特殊情況的應付

甲、不要碰觸包裝表面損壞之部分

乙、表面損壞之部分附近需要做隔離

丙、盡量減少通過時間

4. 需要之設備

甲、嘎瑪線測量器

乙、阿法汙染檢查表

丙、中子測試表

丁、手持式劑量計

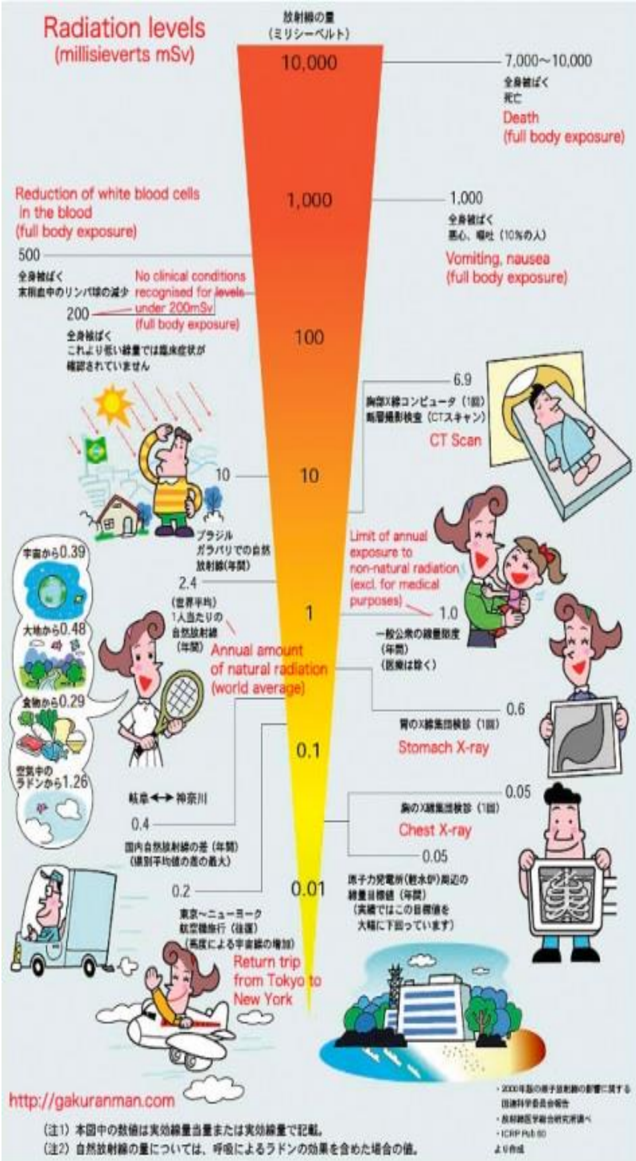
戊、橡膠手套

己、連身衣

庚、防塵口罩

辛、安全玻璃

5. 關於每人可接受輻射的量及其反應:
每人每次照射胸腔X光會接受6.9mSv;
每人每年可接受之輻射量為50mSv.
其餘請見下圖:



Radiation levels
(millisieverts mSv)
放射線の量
(ミリシーベルト)
10,000
1,000
100
10
1
0.1
0.01
7,000~10,000
全身被ばく
死亡
Death
(full body exposure)
1,000
全身被ばく
悪心、嘔吐（10%の人）
Vomiting, nausea
(full body exposure)
Reduction of white blood cells
in the blood
(full body exposure)
500
全身被ばく
末梢血中のリンパ球の減少
No clinical conditions
recognised for levels
under 200mSv
(full body exposure)
200
全身被ばく
これより低い線量では臨床症状が
確認されていません
6.9
胸部X線コンピュータ（1回）
断層撮影検査（CTスキャン）
CT Scan
10
ブラジル
ガラパリでの自然
放射線(年間)
宇宙から0.39
大地から0.48
食物から0.29
空気中の
ラドンから1.26
2.4
(世界平均)
1人当たりの
自然放射線
(年間)
Annual amount
of natural radiation
(world average)
Limit of annual
exposure to
non-natural radiation
(excl. for medical
purposes)
1.0
一般公衆の線量限度
(年間)
(医療は除く)
0.6
胃のX線集団検診（1回）
Stomach X-ray
0.05
胸のX線集団検診（1回）
Chest X-ray
0.05
原子力発電所(軽水炉)周辺の
線量目標値（年間）
(実績ではこの目標値を
大幅に下回っています)
岐阜 ↔ 神奈川
0.4
国内自然放射線の差（年間）
(県別平均値の差の最大)
0.2
東京~ニューヨーク
航空機旅行（往復）
(高度による宇宙線の増加)
Return trip
from Tokyo to
New York
http://gakuranman.com
(注1) 本図中の数値は実効線量当量または実効線量で記載。
(注2) 自然放射線の量については、呼吸によるラドンの効果を含めた場合の値。

網址:
http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Transport/Transport-of-Radioactive-Materials/ *(Updated August 2014)*

資料翻譯如下:

- **About twenty million consignments of all sizes containing radioactive materials are routinely transported worldwide annually on public roads, railways and ships.**
  全球每年大約有兩千萬個帶有放射性物料運送合約經由道路、鐵道及水路運輸至各地。
- **These use robust and secure containers. At sea, they are generally carried in purpose-built ships.**
  在海上一般均由特種船舶裝運這些堅實且安全的貨櫃,
- **Since 1971 there have been more than 20 000 shipments of used fuel and high-level wastes (over 80 000 tonnes) over many million kilometres.**

從 1971 年起有超過 20,000 個海上運送契約且超過八萬噸的高污染核廢料被運輸超過好幾百萬公里.

- **There have been accidents over the years, but never one in which a container with highly radioactive material has been breached, or has leaked.**

  但是其中沒有任何放射性物質曾經發生過洩漏事故。

About 20 million consignments of radioactive material (which may be either a single package or a number of packages sent from one location to another at the same time) take place around the world each year. Radioactive material is not unique to the nuclear fuel cycle and only about 5% of the consignments are fuel cycle related. Radioactive materials are used extensively in medicine, agriculture, research, manufacturing, non-destructive testing and minerals' exploration.

每年約有兩千萬個放射性物質運送契約在世界各地運送，放射性物質不一定有核燃料反應，其中約只有百分之五的貨物是與核燃料

有關。放射性物質被廣泛用於醫藥、農業、科學研究、製造、非破壞性檢測與礦物質探測。

International regulations for the transport of radioactive material have been published by the International Atomic Energy Agency (IAEA) since 1961. These regulations have been widely adopted into national regulations, as well as into modal regulations, such as the International Maritime Organisation's (IMO) Dangerous Goods Code. Regulatory control of shipments of radioactive material is independent of the material's intended application.

國際原子能總署（IAEA）於 1961 年公佈國際放射性物質運輸規則，至今已被全球廣泛地採用並成為國內法或規範；如預期般地放射性物質運輸的監管是獨立於其他物質，例如國際海事組織（IMO）之危險品章程(IMDG CODE)。

Nuclear fuel cycle facilities are located in various parts of the world and materials of many kinds need to be transported between them. Many of these are similar to materials used in other industrial activities. However, the nuclear industry's fuel and waste materials are radioactive, and it is these 'nuclear materials' about which there is most public concern.

核燃料反應廠分佈於世界各地，但原料大多產於其他地區，因此需要進行運輸作業，其中有許多是運用於相類似之其他工業所用的材料。然而正是這些核工業的放射性燃料及廢料，引起大多數人的關切。

Nuclear materials have been transported since before the advent of nuclear power over fifty years ago. The procedures employed are designed to ensure the protection of the public and the environment both routinely and when accidents occur. For the generation of a given quantity of electricity, the amount of nuclear fuel required is very much smaller than the amount of any other fuels. Therefore, the conventional risks and environmental impacts associated with fuel transport are greatly reduced with nuclear power.

距今五十年前核電被廣泛應用時，運送核物質就已經在進行了。當時為防止意外發生，

採用確保公眾安全與環境保護的運送程序。與其他發電型式相比，為產生相同電量所需消耗燃料，核燃料的需要量比任何其它燃料的量要少，因此大大地降低了燃料運輸之傳統風險與環境影響。

In the USA one percent of the 300 million packages of hazardous material shipped each year contain radioactive materials. Of this, about 250,000 contain radioactive wastes from US nuclear power plants, and 25 to 100 packages contain used fuel. Most of these are in robust 125-tonne Type B casks carried by rail, each containing 20 tonnes of used fuel.

在每年運往美國 300 萬件有害物質物中，只有百分之一是含有放射性物質的。另外，從美國的核電廠運出大約有 25 萬件含有放射性廢棄物，以及 25 至 100 件使用過的放射性燃料。其中大部分放射性物質是以能裝載 125 噸之堅固桶裝容器填裝 20 噸後再經由鐵路運輸出境。

12.5 噸桶裝容器

Materials being transported
核物料的運送

Transport is an integral part of the nuclear fuel cycle. There are some 430 nuclear power reactors in operation in 32 countries but uranium mining is viable in only a few areas. Furthermore, in the course of over forty years of operation by the nuclear industry, a number of specialised facilities have been developed in various locations around the world to provide fuel cycle services. Hence there is a need to transport nuclear fuel cycle materials to and from these facilities. Indeed, most of the material used in nuclear fuel is transported several times during its its progress through the fuel cycle. Transport is frequently international, and often over large distances. Any substantial quantities of radioactive materials are generally transported by specialised transport companies.

運輸是核足跡中的一部分，全球約有 430 座運轉中之核能電廠，其分佈於 32 個國家中，但鈾礦的開採只有在少數幾個地區。此外，在四十多年前核工業發展過程中，一些專門的設施已在世界各地不同地點展開運送核燃料與相關作業服務，也產生核足跡。事實上大多數核燃料均被運送多次，同時交通運輸是國際性且運送距離長，因此任何放射性物質均由專門的運輸公司負責運送。

The term 'transport' is used in this document only to refer to the movement of material between facilities, i.e. through areas outside such facilities. Most consignments of nuclear fuel material occur between different stages of the cycle, but occasionally material may be transported between similar facilities. When the stages are directly linked (such as mining and milling), the facilities for the different stages are usually on the same site, and no transport is then required.

每個運送之核物質均處於不同階段之核足跡，但偶爾會有相同階段性核物質之運送，或用在不同階段但設備設置在同一地點，如採礦和加工因有直接關聯性因此沒有運送的必要。

With very few exceptions, nuclear fuel cycle materials are transported in solid form. The following table shows the principal nuclear material transport activities:

除少數例外，核燃料均以固態形式運輸。下表列出主要的核物質運輸活動：

運送地	目的地	材質	備註
礦區	工廠	鐵	幾乎在同廠區
工廠	轉化	濃縮鈾氧化物	200 L 桶裝置於標準 6 米運輸貨櫃中
轉化	濃縮	UF6	特殊 UF6 貨櫃
濃縮	燃料元素製造	濃縮 UF6	特殊 UF6 貨櫃
燃料製造	發動電力	未使用過之鈾	
發動電力	使用料之儲存	使用過之燃料	廠內儲存槽使用 B 型櫃
儲存料	廢料丟棄	使用過之燃料	B 型櫃
儲存料	重新使用	使用過之燃料	
重新使用	轉化	鈾氧化物	RepU
重新使用	燃料製造	二氧化鈽	
重新使用	廢料丟棄	裂變產物	玻化
所有設備	儲存丟棄	廢棄物	通常在同一廠區

公式說明 UO_2 的由來

UF_6	+	$2H_2O$	→	UO_2F_2	+	4HF
(gas)		(Excess steam)		(solid)		(gas)
UO_2F_2	+	H_2	→	UO_2	+	2HF
(solid)				(powder)		(gas)

Although some waste disposal facilities are located adjacent to the facilities that they serve, utilising one disposal site to manage the wastes from several facilities usually reduces environmental impacts. When this is the case, transport of the wastes from the facilities to the disposal site will be required.

雖然有些廢物處置機構與他們相關處置設施毗鄰，共用一個處置場管理廢棄物通常會減少對環境的影響，但是這種情況亦需要從設備到處理場間的廢物運輸。

Classification of radioactive wastes

核廢料之分類

- Exempt waste - excluded from regulatory control because radiological hazards are negligible.

免除監管廢棄物：可以排除監管控制，因其輻射危害可以忽略不計。

- Low-level waste (LLW) - contains enough radioactive material to require action for the protection of people, but not so much that it requires shielding in handling or storage.

低放射性廢棄物（LLW）： 包含足夠量的放射性物質，要求對人要有保護動作，需要遮蔽處理或存儲但量很少。

- Intermediate-level waste (ILW) - requires shielding. If it has more than 4000 Bq/g of long-lived (over 30 year half-life) alpha emitters it is categorised as "long-lived" and requires more sophisticated handling and disposal.

中放射性廢棄物（ILW）： 需要遮蔽處理。如果輻射量超過 4000 Bq/g 且半衰期超過 30 年，例如 α 粒子則被歸類為長週期輻射，需要更複雜的處理和處置。

- High-level waste (HLW) - sufficiently radioactive to require both shielding and cooling, generates >2 kW/m^3 of heat and has a high level of long-lived alpha-emitting isotopes.

高放射性廢棄物（HLW）： 有大量的放射性，同時需要遮蔽與散熱，所產生的熱量大於 2 KW/M^3，並具有大量長週期的 α 粒子同位素。

Packaging
包裝

The principal assurance of safety in the transport of nuclear materials is the design of the packaging, which must allow for foreseeable accidents. The consignor bears primary responsibility for this. Many different nuclear materials are transported and the degree of potential hazard from these materials varies considerably. Different packaging standards have been developed by the IAEA according to the charactristics and potential hazard posed by the different types of nuclear material, and regardless of the mode of transport.

核物料運輸安全主要取決於包裝容器，容器的設計必須能承受可預期到的事故，因此出貨人應為此承擔主要責任。不同核物料運輸所潛在的危險差異因包裝容器程度不同而有所差異。國際原子能機構根據核物料特徵研究與其類型可能帶來的危害，不論運輸方式為何制定了不同的包裝容器標準。

Ordinary industrial containers are used for low-activity material such as uranium oxide concentrate shipped from mines - U3O8. About 36 standard 200-litre drums fit into a standard 6-metre transport container. They are also used for low-level wastes within countries.

從礦區運送出來的低輻射性物質如濃縮的氧化鈾- U_3O_8，一般使用工業性容器包裝，約 36 個 200 公升標準桶放入一個標準 6 米長的運輸槽櫃。此容器也常用於國內低放射性廢料的運輸。

'Type A' packages are designed to withstand minor accidents and are used for medium-activity materials such as medical or industrial radioisotopes.

“A 型”包裝容器的設計是能承受輕微事故，一般用於中等放射性的物質，如醫用或工業用放射性同位素。

Containers for high-level waste (HLW), used fuel and MOX fuel are robust and very secure casks known as 'Type B' packages. They range from drum-size to truck-size and maintain shielding from gamma and neutron radiation, even under extreme accident conditions. Designs are certified by national authorities. There are over 150 kinds of Type B packages, and the larger ones cost some US$1.6 million each.

裝載高放射性廢料的貨櫃（HLW），是使用堅固且非常安全的桶裝容器；其中可以裝載核廢料和 MOX 者，被稱之為“B 型”的桶裝容器，容量從滾筒到卡車般大小，其結構可遮蔽伽馬和中子輻射，且能在遭受極端事故時保持結構完整性，包容的整體設計是由國家主管部門認證。所有 B 型包裝容器中約有 150 多種，以及較大型包裝容器，每個容器的造價都在 160 萬美元左右。

B 型桶裝容器

In France alone, there are some 750 shipments each year of Type B packages. This is in relation to 15 million shipments classified as 'dangerous goods', 300,000 of which are radioactive materials of some kind.

在法國每年約有 750 個 B 型桶裝容器運輸出國。在一千五百萬個被歸類為“危險品”的運送合約中，就有三十萬個是某種形式的放射性物質。

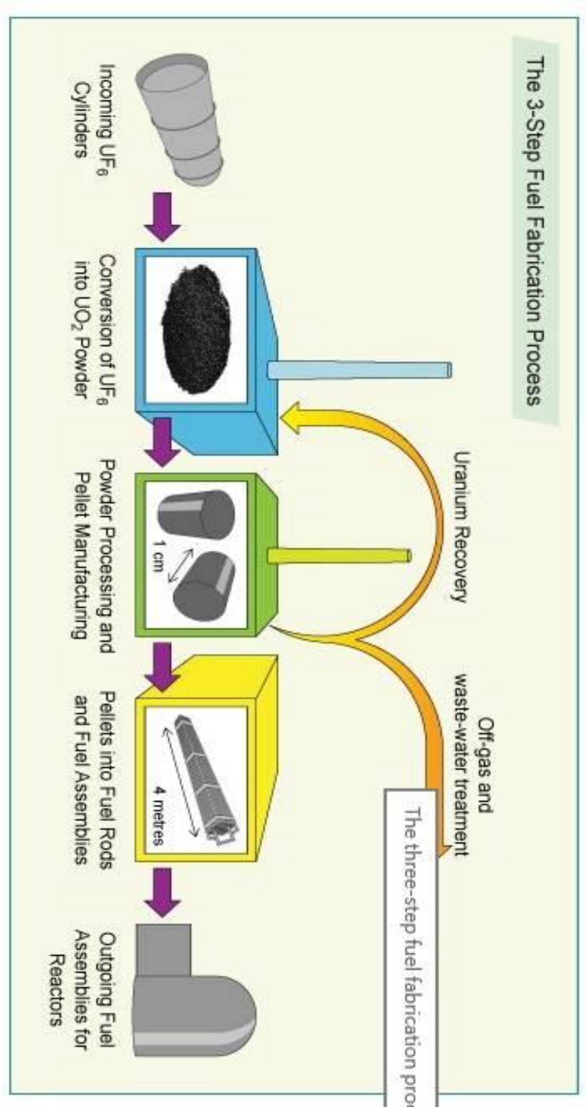
Smaller amounts of high-activity materials (including plutonium) transported by aircraft are be in 'Type C' packages, which give even greater protection in all respects than Type B packages in accident scenarios. They can survive being dropped from an aircraft at cruising altitude.

包括鈽在內的高度活性原料僅有少量是交付空運，他們是使用“C 型”桶裝容器，此容器在各方面比 B 型桶裝容器有更大運輸保障。“C 型”桶裝容器能承受自飛機巡航高度下自由落下後的損傷。

An example of a Type B shipping package is Holtec’s HI-STAR 80 cask (STAR = storage, transport and repository), a multi-layered steel cylinder which holds 12 PWR or 32 BWR high-burnup used fuel assemblies (above 45 GWd/t) which have had cooling times as short as 18 months. The HI-STAR 60 can transport 12 PWR used fuel assemblies, and two aluminium impact limiters. The HI-STAR 180 was the first one licensed to transport high-burnup fuel, and holds 32 or 37 PWR used fuel assemblies. The HI-STAR 190 cask has the world’s highest heat load capacity, at 38 kW, and is to be used domestically in Ukraine for PWR fuel. The HI-STAR 100 is based on a sealed multi-purpose canister containing the fuel which can be transferred to HI-STORM storage systems, exchanging one overpack for another.

HOLTEC 的 HI-STAR 80 桶是一種標準 B 型具有多層次的運輸鋼瓶，可以裝載 12 PWR(Pressurized Water Reactor 加壓水式反應器)或 32 BWR(Boiling Water Reactor 沸騰水式反應器)的高燃耗組件（超過 45 Giga-watt days per tonne），容器可接受少於 18 個月的冷卻時間。

HI-STAR 180 桶裝容器結構


The 3-Step Fuel Fabrication Process
Incoming UF_6 Cylinders
Conversion of UF_6 into UO_2 Powder
Powder Processing and Pellet Manufacturing
1 cm
Pellets into Fuel Rods and Fuel Assemblies
4 metres
Outgoing Fuel Assemblies for Reactors
Uranium Recovery
Off-gas and waste-water treatment
The three-step fuel fabrication pro

燃料製造的三個程序

HI-STAR 60 是可以運輸 12 PWR 使用的燃料組件，具有兩個鋁質的撞擊緩衝器。HI-STAR 180 是第一個許可能填裝高燃耗燃料，並擁有 32 或 37 PWR 所使用的燃料組件。HI-STAR 190 在設計上，具有世界上最高的熱負荷能力(38 千瓦)，使用在烏克蘭國內運送 PWR 燃料。HI-STAR 100 是一種密封式多用途桶裝容器，可以在高存儲系統內作運輸。

Radiation protection

輻射防護

When radioactive materials, including nuclear materials, are transported, it is important to ensure that radiation exposure of both those involved in the transport of such materials and the general public along transport routes is limited. Packaging for radioactive materials includes, where appropriate, shielding to reduce potential radiation exposures. In the case of some materials, such as fresh uranium fuel assemblies, the radiation levels are negligible and no shielding is required. Other materials, such as used fuel and high-level waste, are highly radioactive and purpose-designed containers with integral shielding are used. To limit the risk in handling of highly radioactive materials, dual-purpose containers (casks), which are appropriate for both storage and transport of used nuclear fuel, are often used.

在運送放射性物質其中包括核物料，為確保在大眾運輸路線上減少其輻射曝露，放射性物質的包裝材料應能在適當情況下，屏蔽潛在的輻射釋放。有些輻射物料，例如裝載未使用過的鈾燃料組件時，其輻射含量通常是可以忽略不計的，不需要屏蔽。但其它的物料，如核燃料或高放射性廢棄物，裝載容器則需設計成具有整體屏蔽效果。為了減少高放射性危險，多用途容器經常被使用於存儲及運送。

As with other hazardous materials being transported, packages of radioactive materials are labelled in accordance with the requirements of national and international regulations. These labels not only indicate that the material is radioactive, by including a radiation symbol, but also give an indication of the radiation field in the vicinity of the package. Personnel directly involved in the transport of radioactive materials are trained to take appropriate precautions and to respond in case of an emergency.

如同運送有害物質般，運送放射性物質時其包裝需按照國家和國際法規要求清楚標示。此標示不僅需標明該材料具放射性，並且通透過標示指出會受感染的範圍。同時規定，對直接從事於放射性物質運送的人員，應進行”如何預防”以及”緊急處理”的訓練。

Environmental protection
環境保護

Packages used for the transport of radioactive materials are designed to retain their integrity during the various conditions that may be encountered while they are being transported thus ensuring that an accident will not have any major consequences. Conditions which packages are tested to withstand include: fire, impact, wetting, pressure, heat and cold. Packages of radioactive material are checked prior to shipping and, when it is found to be necessary, cleaned to remove contamination. Although not required by transport regulations, the nuclear industry chooses to undertake some shipments of nuclear material using dedicated, purpose-built transport vehicles or vessels.

用於放射性物料的運輸包裝容器，均設計於輸送過程中遭受事故均不會造成任何嚴重的後果，並保持完容器整性。該包裝容器應進行測試，測試狀況包括：火災，衝擊，受潮，壓力，熱冷交替。放射性物質的包裝容器在裝貨之前必須檢查，當被發現任何異常必須清潔以去除污染源。雖然運輸法規並無明文規定，但核物質產業均使用核物料專用的運輸車輛或船隻。

Regulation of transport
運輸法規

Since 1961 the International Atomic Energy Agency (IAEA) has published advisory regulations for the safe transport of radioactive material. These regulations have come to be recognised throughout the world as the uniform basis for both national and international transport safety requirements in this area. Requirements based on the IAEA regulations have been adopted in about 60 countries, as well as by the International Civil Aviation Organisation (ICAO), the International Maritime Organisation (IMO), and regional transport organisations.

自 1961 年以來國際原子能總署（IAEA）發布了放射性物質安全運輸法規。這些規定已逐漸被世界認可，並作為此一領域的國內和國際運輸安全規定的基礎。國際原子能機構的規定，有約 60 個國家，以及國際民用航空組織（ICAO），國際海事組織（IMO）和區域交通組織所採用。

The IAEA has regularly issued revisions to the transport regulations in order to keep them up to date. The latest set of regulations is published as TS-R-1, *Regulations for the Safe Transport of Radioactive Material*, 2009 Edition.

國際原子能總署均定期發佈最新版本運輸規定，例如 2009 年發布規則 TS-R-1，”放射性物質安全運輸規則”。

The objective of the regulations is to protect people and the environment from the effects of radiation during the transport of radioactive material.

法規訂定的目標是為確保放射性物質在運輸過程中，保護人們和環境遠離輻射影響。

Protection is achieved by:

保護措施可藉由下列方式達成：

- containment of radioactive contents;
  輻射物質的包裝
- control of external radiation levels;
  外部的控制等級
- prevention of criticality; and
  如何防止發生臨界狀態
- prevention of damage caused by heat.
  如何防止對於熱所造成的損害

The fundamental principle applied to the transport of radioactive material is that the protection comes from the design of the package, regardless of how the material is transported.

對於放射性物質於運輸過程中所採取的保護措施，其基本原理是取決於包裝容器的設計，並非物質的運輸方式。

Transport of uranium oxide from mines and uranium hexafluoride

氧化鈾與六氟化鈾開採後的運送

Uranium oxide concentrate, sometimes called yellowcake, is transported from the mines to conversion plants in 200-litre drums packed into normal shipping containers. No radiation protection is required beyond having the steel drums clean and within the shipping container.

氧化鈾的濃縮物，有時也被稱為黃餅，從礦場運到罐裝工廠中裝入 200 升的桶裝容器，再將容器置入一般運輸貨櫃。假由低輻塵量鋼桶容器與運輸貨櫃的保護，於運輸時並需其他輻射防護措施。

In Australia, over more than three decades to 2014, 11,000 shipping containers with drums of U_3O_8 were moved from mines to ports with no incident affecting public health.

至 2014 年止在澳洲超過三十年間，共有 11,000 個海運貨櫃與 U_3O_8 的容量自礦場運送至港口，並沒有發生任何影響公眾健康的事故。

To and from enrichment plants, the uranium is in the form of uranium hexafluoride (UF6), which again is barely radioactive but has significant chemical toxicity. It is in special containers, which also function for storage.

回到濃縮工廠裏，鈾礦是以六氟化鈾的形式存在（UF6）幾乎沒有放射性，但是有顯著的化學毒性，鈾礦在工廠內均存放在設計成專為儲放用的特殊容器裏。

Transport of uranium fuel assemblies
鈾燃料組的運輸

Uranium fuel assemblies are manufactured at fuel fabrication plants. The fuel assemblies are made up of ceramic pellets formed from pressed uranium oxide that has been sintered at a high temperature (over 1400℃). The pellets are aligned within long, hollow, metal rods, which in turn are arranged in the fuel assemblies, ready for introduction into the reactor.

鈾燃料組由燃料製造廠製造，燃料棒是由氧化鈾在攝氏 1400 高溫下燒結擠壓形成陶瓷

小球而製成，再將粒料置入中空金屬棒上，最後製作成燃料組用於置入反應爐內。

Different types of reactors require different types of fuel assembly, so when the fuel assemblies are transported from the fuel fabrication facility to the nuclear power reactor, the contents of the shipment will vary with the type of reactor receiving it.

不同類型的反應器需使用不同類型的燃料組，因此燃料組會由燃料製造廠，依反應爐的類型運送到各核電廠內。

In Western Europe, Asia and the US, the most common means of transporting uranium fuel assemblies is by truck. A typical truckload supplying a light water reactor contains 6 tonnes of fuel. In the countries of the former Soviet Union, rail transport is most often used. Intercontinental transports are mostly by sea, though occasionally transport is by air.

在西歐、亞洲和美國，最常用運送鈾燃料組的方式是通過卡車，卡車內通常整車裝載 6 噸提供輕水反應爐所使用的燃料組。在原蘇聯

的國家，通常運用鐵路運輸，洲際間大多透過海運，偶爾使用航空運輸。

The annual operation of a 1000 MWe light water reactor requires an average fuel load of 27 tonnes of uranium dioxide, containing 24 tonnes of enriched uranium, which can be transported in 4 to 5 trucks.

一座 1000MW 的輕水反應爐，平均年需求量為 27 噸二氧化鈾，其由包含 24 噸濃縮鈾，此需求量可經由 4 至 5 部卡車運輸。

The precision-made fuel assemblies are transported in packages specially constructed to protect them from damage during transport. Uranium fuel assemblies have a low radioactivity level and radiation shielding is not necessary.

精鍊過的燃料組在運輸時是裝置在專門設計的包裝容器內，以確保在運輸過程中不致受損，鈾燃料組具有低放射性因此不需額外的輻射屏蔽。

Fuel assemblies contain fissile material and criticality is prevented by the design of the package, (including the arrangement of the fuel assemblies within it, and limitations on the amount of material contained within the package), and on the number of packages carried in one shipment.

燃料組包含可裂解原素與臨界狀態，為防止產生作用可籍由包裝容器來達成，其中由包括燃料組的佈置，以及在包裝容器內的件數，並限制在運輸時能同時運送之包裝容器數量。

Transport of LLW and ILW
低級與中級放射性廢棄物的運送

Low-level and intermediate-level wastes (LLW and ILW) are generated throughout the nuclear fuel cycle and from the production of radioisotopes used in medicine, industry and other areas. The transport of these wastes is commonplace and they are safely transported to waste treatment facilities and storage sites.

低級(LLW)和中級(ILW)放射性廢棄物在整個核燃料足跡中，是由生產醫藥所使用的放射性同位素與核能工業等領域所產生的。這些

廢棄物的運輸是司空見慣，他們被安全運送到垃圾處理廠與儲存地點。

Low-level radioactive wastes are a variety of materials that emit low levels of radiation, slightly above normal background levels. They often consist of solid materials, such as clothing, tools, or contaminated soil. Low-level waste is transported from its origin to waste treatment sites, or to an intermediate or final storage facility.

低放射性廢棄物中，其各種樣的輻射量很低，但略高於正常生活背景，包括固體物質，如衣物、工具或污染的土壤。低放射性廢棄物的運輸過程通常為，由起源運送至廢棄物處理場或者到中間或最終的儲存設施。

A variety of radionuclides give low-level waste its radioactive character. However, the radiation levels from these materials are very low and the packaging used for the transport of low-level waste does not require special shielding.

多種放射性原素給予低放射性廢棄物的放射性特質，然而從這些物質中所產生的輻射

量非常低，因此只需使用低放射性廢棄物的運輸包裝，不需特殊屏蔽。

Low-level wastes are transported in drums, often after being compacted in order to reduce the total volume of waste. The drums commonly used contain up to 200 litres of material. Typically, 36 standard, 200 litre drums go into a 6-metre transport container. Low-level wastes are moved by road, rail, and internationally, by sea. However, most low-level waste is only transported within the country where it is produced.

低放射性廢棄物運送一般儲放於桶裝容器內，通常被壓縮以減少廢棄物的體積。常用的桶裝容器高達 200 公升的容積，通常 36 個標準 200 公升桶裝容器可裝入一個二十呎貨櫃。低放射性廢棄物是經由公路或鐵路運輸，或經海上輸送至其他國家，然而大多數低放射性廢棄物只在生產國內運輸。

The composition of intermediate-level wastes is broad, but they require shielding. Much ILW comes from nuclear power plants and reprocessing facilities.

中放射性廢棄物的來源非常廣泛，因此需要的屏蔽。由其來源大多來自於核電廠與後端處理廠。

Intermediate-level wastes are taken from their source to an interim storage site, a final storage site (as in Sweden), or a waste treatment facility. They are transported by road, rail and sea.

中放射性廢棄物由產生地至臨時存儲地、最終存儲地或廢棄物處理廠，通常籍由公路、鐵路或海上運輸。

The radioactivity level of intermediate-level waste is higher than low-level wastes. The classification of radioactive wastes is decided for disposal purposes, not on transport grounds. The transport of intermediate-level wastes take into account any specific properties of the material, and requires shielding.

中放射性廢棄物的放射性強度高於低放射性廢棄物。放射性廢棄物的分類決定處置的

目的，而不是以運輸方式。中放射性廢棄物的運輸因考量到廢棄物的特性，因此需要屏蔽。

In the USA there had been 9000 road shipments of defence-related transuranic wastes for permanent disposal in the deep geological repository near Carlsbad, New Mexico, by October 2010, without any major accident or any release of radioactivity. Almost half the shipments were from the Idaho National Laboratory. The repository, known as the Waste Isolation Pilot Plant (WIPP), is about 700 m deep in a Permian salt formation.

2010 年 10 月在美國曾有過與國防有關的九千件超鈾廢棄物經由公路運輸至新墨西哥州卡爾斯巴德城鎮附近永久儲放於深層貯存庫內，而無任何重大事故或放射性污染發生，其中一半的數量是從愛達荷國家實驗室產生。貯存庫被稱為廢棄物隔離廠，大約在地底下 700 米深的二疊紀鹽層。

Transport of used nuclear fuel
使用過核燃料的運送

When used fuel is unloaded from a nuclear power reactor, it contains: 96% uranium, 1% plutonium and 3% of fission products (from the nuclear reaction) and transuranics).

使用過的核燃料是由核子反應器卸下，其中含有 96%的鈾，1%鈽和 3%的裂變產生物與超鈾元素）。

Used fuel will emit high levels of both radiation and heat and so is stored in water pools adjacent to the reactor to allow the initial heat and radiation levels to decrease. Typically, used fuel is stored on site for at least five months before it can be transported, although it may be stored there long-term.

使用過的核燃料會散發出高強度的輻射與熱能，因此通常存儲在與反應器相鄰的水池內，以減少在初始熱能與輻射量。雖然使用過的核燃料可以長期存儲在廠房內，但通常在可以運輸上路前，使用過的核燃料至少儲存在反應爐廠房內 5 個月以上。

From the reactor site, used fuel is transported by road, rail or sea to either an interim storage site or a reprocessing plant where it will be reprocessed.

使用過的核燃料從反應器的廠內通過公路、鐵路或海上運輸到任何一個臨時貯存場地或後端處理廠進行再加工。

Used fuel assemblies are shipped in Type B casks which are shielded with steel, or a combination of steel and lead, and can weigh up to 110 tonnes when empty. A typical transport cask holds up to 6 tonnes of used fuel.

使用過的燃料組運送時均裝置於籍由鋼或鋼鉛混合達到屏蔽效果的 B 型桶裝容器，此容器重達 110 噸，桶裝容器可裝載多達 6 噸的燃料組。

Since 1971 there have been some 7000 shipments of used fuel (over 80 000 tonnes) over many million kilometres with no property damage or personal injury, no breach of containment, and very low dose rate to the personnel involved (e.g. 0.33 mSv/yr per operator at La Hague). This includes 40,000 tonnes of used fuel shipped to

Areva's La Hague reprocessing plant, at least 30,000 tonnes of mostly UK used fuel shipped to UK's Sellafield reprocessing plant, 7140 t used fuel in 160 shipments from Japan to Europe by sea (see below) and 4500 tonnes of used fuel shipped around the Swedish coast.

1971 年以來出超過 7000 件運輸，運送 80 萬噸以上使用過核燃料，運行距離超過百萬公里，但其中並沒有造成財產損失或人員傷害與環境污染，只對工作人員造成非常低劑量的輻射感染。這其中包括 40,000 噸使用過核燃料運到 Areva’s La Hague 後端處理廠，30,000 噸英國使用過核燃料運到英國 Sellafield 後端處理廠，7,140 噸使用過核燃料藉由 160 艘次由日本經海上運輸至歐洲，4,500 使用過核燃料運往瑞典海岸。

Some 300 sea voyages have been made carrying used nuclear fuel or separated high-level waste over a distance of more than 8 million kilometres. The major company involved has transported over 4000 casks, each of about 100 tonnes, carrying 8000 tonnes of used fuel or separated high-level wastes. A quarter of these have been through the Panama Canal.

在 300 次海上運輸中，已運送使用過核燃料或已離析的高放射性廢棄物超過 800 多萬公里。每一季航運公司運送 4,000 多桶每桶約 100 噸，運載 8,000 噸使用過核燃料或已離析的高放射性廢棄物通過巴拿馬運河。

In Sweden, more than 80 large transport casks are shipped annually to a central interim waste storage facility called CLAB. Each 80 tonne cask has steel walls 30 cm thick and holds 17 BWR or 7 PWR fuel assemblies. The used fuel is shipped to CLAB after it has been stored for about a year at the reactor, during which time heat and radioactivity diminish considerably. Some 4500 tonnes of used fuel had been shipped around the coast to CLAB by the end of 2007.

在瑞典每年有超過 80 個大型桶裝容器，運到到中央臨時廢棄物貯存廠。每個桶裝容器有 80 噸重鋼壁厚達 30 公分，能裝載 17 BWR 和 7PWR 的燃料組。自 2007 年開 4500 噸使用過核燃料在反應爐廠內儲存一年後，因熱能與

放射能量減少很多，才被運送到中央臨時廢棄物貯存廠。

Shipments of used fuel from Japan to Europe for reprocessing used 94-tonne Type B casks, each holding a number of fuel assemblies (e.g. 12 PWR assemblies, total 6 tonnes, with each cask 6.1 metres long, 2.5 metres diameter, and with 25 cm thick forged steel walls). More than 160 of these shipments took place from1969 to the 1990s, involving more than 4000 casks, and moving several thousand tonnes of highly radioactive used fuel - 4200t to UK and 2940t to France. Within Europe, used fuel in casks has often been carried on normal ferries, e.g. across the English Channel.

使用過的核燃料由日本運送到歐洲再進行加工處理，均使用 94 噸 B 型桶裝容器，每桶裝載一件燃料組，每個容器長 6.1 公尺，口徑 2.5 公尺，桶壁厚達 25 公分由鍛鋼製造。 自 1969 年到 90 世紀多達 160 件運送合約，運輸超過 4,000 桶，運載幾千噸高放射性使用過核燃料，其中 4,200 噸運送至英國 2,940 噸運至

法國。在歐洲，使用過核燃料均使桶裝容器裝載，由商船運送橫渡英吉利海峽。

Transport of plutonium
鈽的運送

Plutonium is separated during the reprocessing of used fuel. It is normally then made into mixed oxide (MOX) fuel. Plutonium is transported, following reprocessing, as an oxide powder since this is its most stable form. It is insoluble in water and only harmful to humans if it enters the lungs.

鈽是經由使用過核燃料經再處理過程後離析而得。鈽通常被再製成混合氧化物燃料，鈽經處理後才能輸送，因氧化粉末狀是其最穩定的形式。鈽不溶於水但吸入肺部時對人體將產生危害。

Plutonium oxide is transported in several different types of sealed packages and each can contain several kilograms of material. Criticality is prevented by the design of the package, limitations on the amount of material contained within the package, and on the number of packages carried on a transport vessel. Special physical protection measures apply to plutonium consignments.

鈽氧化物被裝入幾種不同類型的密封包裝容器中，每個容器可以裝載數公斤鈽製品。藉由封裝與限制裝載數量的設計以防止鈽產生臨界狀態，同時限制船上能運送的容器數量，運載鈽時工作人員亦需實施特定的保護措施。

A typical transport consists of one truck carrying one protected shipping container. The container holds a number of packages with a total weight varying from 80 to 200 kg of plutonium oxide. A sea shipment may consist of several containers, each of them holding between 80 to 200 kg of plutonium in sealed packages.

通常鈽的運送經由卡車載運具防護設計的貨櫃，每個貨櫃能裝載 80 至 200 公斤氧化鈽。海上運輸時可同時載運數個貨櫃，每個貨櫃內可裝載 80 至 200 公斤在密封保裝容器內的氧化鈽。

Transport of vitrified waste

玻化廢棄物的運輸

The highly radioactive wastes (especially fission products) created in the nuclear reactor are segregated and recovered during the reprocessing operation. These wastes are incorporated in a glass matrix by a process known as 'vitrification', which stabilises the radioactive material.

在核子反應爐中產生的高放射性廢棄物被離析後，尤其是裂變產物，被送往後端處理操作中回收，這些廢棄料被玻化後，穩定了放射性質同時可與玻璃基結合。

The molten glass is then poured into a stainless steel canister where it cools and solidifies. A lid is welded into place to seal the canister. The canisters are then placed inside a Type B cask, similar to those used for the transport of used fuel.

熔融玻璃後倒入不銹鋼罐內冷卻硬化，焊上蓋子加以密封，然後將該罐置入類似用於運輸使用運核燃料的 B 型桶裝容器內。

The quantity per shipment depends upon the capacity of the transport cask. Typically a vitrified waste transport cask contains up to 28 canisters of glass.

每次運送數量取決於桶裝容器的容量，通常玻化廢棄物運送桶可容納多達 28 個玻璃罐。

Return nuclear waste shipments from Europe to Japan since 1995 are of vitrified high-level wastes in stainless steel canisters. Up to 28 canisters (total 14 tonnes) are packed in each 94-tonne steel transport cask, the same as used for irradiated fuel. Over 1995-2007 twelve shipments were made from France of vitrified HLW comprising 1310 canisters containing almost 700 tonnes of glass. Return shipments from the UK are due to commence, and there will be about 11 shipments over eight years.

自 1995 年以來從歐洲運送到日本的不銹鋼罐裝玻化高放射性核廢料的出貨量，計有 28 罐以上約 14 噸，分別裝在每個 94 噸重的鋼製運輸桶裝容器內，用為輻照燃料。在 1995-2007 年的 12 年間分別來自法國玻化高放射性廢棄

物出貨量，包括 1310 罐含有近 700 噸的玻璃製品。英國開啟此種運輸，超過八年間共有 11 次的運輸。

Purpose-built ships
特殊專用船

In 1993, the International Maritime Organisation (IMO) introduced the voluntary Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships (INF Code), complementing the IAEA Regulations. These complementary provisions mainly cover ship design, construction and equipment. The INF Code came into force in January 2001 and introduced advanced safety features for ships carrying used fuel, MOX or vitrified high-level waste.

1993 年，國際海事組織（IMO）推出瓶裝輻照核燃料、鈽與高放射性廢棄物船上安全運輸章程（Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships; INF Code），用以補充國際原子能機構規定。這

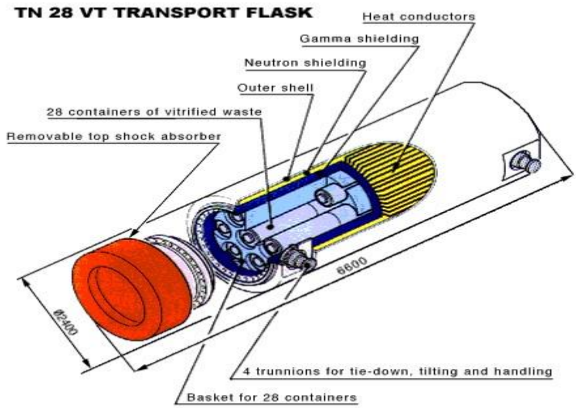
些補充條款主要包括船舶設計、建造與設備。2001 年 1 月 INF 章程生效，並導入先進的安全功能，用於載運使用過燃料，MOX 或玻化高放射性廢棄物。

There are at least five small purpose-built ships ranging from 1250 to 2200 tonnes (DWT), and four purpose-built ships almost of 3800 to 4900 tonnes (DWT), and able to carry class B casks and other materials. They conform to all relevant international safety standards, notably INF-3 (Irradiated Nuclear Fuel class 3) set by the IMO. This allows them to carry highly radioactive materials such as high-level wastes and used nuclear fuel, as well as mixed-oxide (MOX) fuel and plutonium.

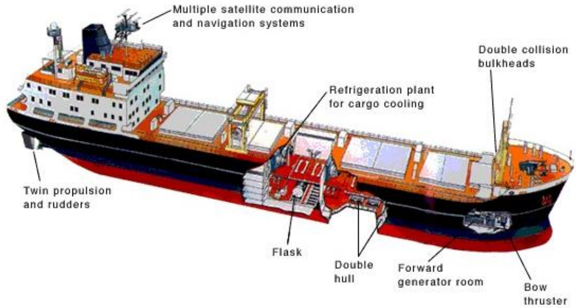
至少有五艘小型的專用船舶載重噸為 1250 至 2200 噸，與四艘專門建造的船舶載重噸為 3800 到 4900 噸，能夠載運 B 級桶裝容器與其他物質。這些船舶均符合所有相關的國際安全標準，特別是國際海事組織所規範之輻照核燃料第 3 類，能夠載運高放射性物質，如高放射性廢棄物與使用過核燃料，以及混合氧化物燃料和鈽。

The three largest ships belong to a British-based company Pacific Nuclear Transport Ltd (PNTL)*, and the *Oceanic Pintail* of 3865 tonnes deadweight and 104 metres long is owned by PNTL parent company International Nuclear Services Ltd (INS). They all have double hulls with impact-resistant structures between the hulls, together with duplication and separation of all essential systems to provide high reliability and also survivability in the event of an accident. Twin engines operate independently. Each ship can carry up to 20 or 24 transport casks. The three PNTL vessels now in service, *Pacific Heron*, *Pacific Egret* and *Pacific Grebe*, were launched in Japan in 2008, 2010 and 2010 respectively. They are 4916 tonnes deadweight and 104 metres long. *Pacific Grebe* carries mainly wastes, the other two mainly MOX fuel. *Oceanic Pintail* carries both. Earlier ships in the PNTL fleet mainly carried Japanese used fuel to Europe for reprocessing. The PNTL fleet has successfully completed more than 200 shipments with more than 2000 casks over some 40 years, covering about 10 million kilometres, without any incident resulting in release of radioactivity.

其中三艘最大的船屬於英國一家的公司-“太平洋核子運輸有限公司”(Pacific Nuclear Transport Ltd; PNTL)載重噸，3,865 船長 104 公尺的”*Oceanic Pintail”*則為”國際核服務有限公司”（International Nuclear Services Ltd; INS）所有擁有。這些船舶在雙重船體之間都具有耐衝擊結構，且船上主要系統均備有兩套且分離，以提供高船舶可靠性，也可在發生事故的情況下生存，具備雙引擎但可獨立運作。每艘船最多可搭載 20 或 24 個運輸桶。這三艘服役中的船舶，”*Pacific Heron”*, “*Pacific Egret”*以及”*Pacific Grebe”*，分別在 2008 年、2010 年 2010 年底在日本下水啟航，載重噸為 4916，船長 104 公尺。”*Pacific Grebe”*主要載運廢棄物，其他兩艘則是載運混合氧化物燃料，”*Oceanic Pintail”*則裝載兩種。早期 PNTL 所屬船隊主要運輸日本使用過燃料到歐洲進行加工處理。PNTL 船隊已成功完成超過 200 件運送合約，在 40 年間載運超過 2000 桶使用過燃料，運送距離超 10 萬公里，同時沒有造成放射性物質外漏的任何事故。



TN 28 VT 運輸瓶



專為運輸核燃料用之特種船

Sweden's SKB has commissioned a slightly larger replacement for its 1982 *Sigyn*, the *Sigrid*, launched in Romania in 2012 and designed by Damen Shipyards in Netherlands. It is used for moving used fuel from reactors to the interim waste storage facility. *Sigrid* is equipped with a double hull, four engines and redundant systems for safety and security. It was commissioned in 2013 and carried its first shipment in January 2014. Sigrid is 99.5 metres long and 18.6 metres wide, 1600 deadweight tonnes (DWT) and capable of carrying twelve nuclear waste casks. (*Sigyn* was 1250 tonnes deadweight and carried ten casks. It awaits further assignment.)

瑞典於 2012 年向荷蘭 Damen 船廠訂造更大的專用船*”Sigrid”* 輪以取代，於 1982 年在羅馬尼亞建造的*”Sigyn”* 輪，新訂造船舶用於運送反應爐使用過的燃料至中途廢物貯存廠；*”Sigrid”* 輪為雙船體船，備有四具引擎以及更多的安全與保全系統。*”Sigrid”*輪於 2013 年開始營運,於 2014 載運第一批貨物,*”Sigrid”* 輪長 99.5 公尺，船寬 18.6 公尺，載重噸 1,600 噸，並能搭載 12 件核廢料桶裝容器。

Rosatomflot is operating the 1620 deadweight tonne (DWT) *Rossita*, built in Italy and completed in 2011. It is designed for transporting spent nuclear fuel and materials of decommissioned nuclear submarines from Russian Navy bases in North-West Russia. It will be used on the Northern Sea Route, between Gremikha, Andreyeva Bay, Saida Bay, Severodvinsk and other places hosting facilities which dismantle nuclear submarines. Spent fuel is to be delivered to Murmansk for rail shipment to Mayak. Rosatomflot has the *Serebryanka* (1625 DWT, 102 m long, built 1974) already in service. The *Imandra* (2186 DWT, 130 m long, built 1980) is described as a floating technical base but is reported to be already in service transporting used fuel and wastes from the Nerpa shipyard and Gremikha to Murmansk. (Andreyeva Bay is the primary spent nuclear fuel and radioactive waste storage facility for the Northern Fleet, some 60 km from the Norwegian border. It has about 21,000 spent nuclear fuel assemblies and about 12,000 m^3 of solid and liquid radioactive wastes.)

Rosatomflot 公司營運載重噸為 1,620 的*"Rossita"*輪，該船建造於意大利，並在 2011 年完工，該船設計用於運輸核廢料以及俄羅斯西北部海軍基地退役核子潛艇的材料。該船航

行於北海航線，包含 Gremikha, Andreyeva Bay, Saida Bay 與 Severodvinsk 等地，該地點均設有拆除核子潛艇的設施。Murmansk 所產生的核廢料經由鐵路運送至 Mayak。 Rosatomflot 公司擁有營運中的”*Serebryanka”*輪（1,625 載重噸；船長 102 公司，於 1974 年建造完成）。另一艘*”Imandra”*輪（2,186 載重噸；船長 130 公尺；於 1980 建造完成），則設計為浮動的儲存平台；但據報導，已經開始輸送使用運核燃料和廢棄物自 Nerpa 造船廠和 Gremikha 運往 Murmansk。Andreyeva Bay 是俄羅斯北方艦隊主要的使用過核燃料與放射性廢棄物貯存場，距離挪威邊境約 60 公里遠，大約有 21,000 公噸使用過核燃料組與 12,000 公噸的固態與液態放射性廢棄物。

Rossita is an ice-class vessel and is designed to operate in harsh conditions of the Arctic. The ship is 84 m long and 14 m wide, with two engines, and has two isolated cargo holds holding up to 720 tonnes in total. On board, the radiation monitoring is carried out by both an automated multi-channel system and a set of portable instrumentation. The EUR 70 million vessel was given to Russia as part of Italy’s commitment to the G-8 partnership program for cleaning up naval nuclear wastes, and is designed to cover all needs in spent nuclear fuel and radioactive waste shipments in northwest Russia throughout the entire period of cleaning up these territories

Rossita 是一艘極地航行船舶，其設計可在北極惡劣的條件下工作，該船長 84 公尺寬 14 公尺配備兩具主機，並有兩個獨立的貨艙最多可容納 720 噸的貨物。在船上輻射監測是通過兩套自動多通道系統和一套可攜式儀器進行，該輪價值 7 千萬歐元交給俄羅斯清理海上核廢料，以代行 G8 國夥伴義大利的承諾計劃的一部分，同時包含在俄羅斯西北部所有需要清理核燃料和放射性廢棄物的領土。

Accident scenarios
意外現場

There has never been any accident in which a Type B transport cask containing radioactive materials has been breached or has leaked. For the radioactive material in a large Type B package in sea transit to become exposed, the ship's hold (inside double hulls) would need to rupture, the 25 cm thick steel cask would need to rupture, and the stainless steel flask or the fuel rods would need to be broken open. Either borosilicate glass (for reprocessed wastes) or ceramic fuel material would then be exposed, but in either case these materials are very insoluble.

至今沒有 B 類桶裝容器裝有放射性物質，在運輸時破損或洩露的任何事故發生。對於較大型放射性物質 B 類包裝容器在海上運輸時洩露，位於二重底艙內部的貨艙將會破裂，甚至厚達 25 公分的鋼桶容器也會發生破裂，同時不銹鋼瓶容器或燃料棒將需破裂。硼矽玻璃（用於再處理的廢棄物）或陶瓷燃料物質將會洩漏，但在這種情況下，這些材料是不容易熱溶的。

The transport ships are designed to withstand a side-on collision with a large oil tanker. If the ship did sink, the casks will remain sound for many years and would be relatively easy to recover since instrumentation including location beacons would activate and monitor the casks.

運輸船的設計能承受大型油輪由側面撞擊，如果運輸船沈沒，桶裝容器在很久以後仍可探測到而且容易收回，因為包括位置標桿等儀器將會啟動同時監控桶裝容器的狀態。

Safe Transportation of Spent Nuclear Fuel
使用過核燃料的安全運送

Recently Congress approved the Yucca Mountain site in Nevada for the disposal of High Level Nuclear Waste (HLW), which includes spent nuclear fuel. The U.S. Department of Energy is now authorized to seek licensing of the repository.

最近美國國會批准了位在內華達州的尤卡山場地處理高放射性核廢料，其中包括使用過核燃料，美國能源部門現在授權尋找貯藏庫的許可。

Because spent nuclear fuel is highly radioactive and therefore dangerous, it is a common misconception that its transportation from the nuclear reactor where it originates to the disposal site in Nevada will pose a great hazard and grave risk to the general public.

因為使用過核燃料具高放射性因此非常危險，大眾常誤解認為放射性是來自核反應爐，其實放射性產自位於內華達州的貯藏場，對廣大市民造成很大的危害與嚴重威脅。

However, many materials are dangerous under some circumstances, but by simple control measures, the risks can be eliminated or reduced to acceptable levels.

然而，許多物質在某些情況下非常危險，但透過簡單的控制措施，風險可以被消除或減小到可接受的程度。

Ammonium nitrate, for example, is used safely by the ton as a fertilizer. On the other hand, it can be a terrible explosive.

例如硝酸銨常數以噸計的被安全地作為肥料使用。但也是一種可怕的炸藥。

Just so with spent nuclear fuel. If no provision is made to control the radiation, it is truly "deadly" and exposure at close range for relatively short periods of time can be lethal.

正如同使用過核燃料，如果不利用法規來管控輻射，真是“致命的”，當在短時間內暴露在近距離時可能是致命的。

Fortunately, control of the radiation is done rather simply, by storing or manipulating the spent fuel under water or behind thick layers of iron, lead, or concrete. These "shielding" materials absorb the radiation and eliminate the risk inherent in the unshielded spent fuel.

幸運的是輻射簡單地被控制住了，藉由存儲在水槽或者含厚鐵板或鉛板的混凝土箱函裹，這些“屏蔽”物質吸收輻射，同時也消除缺乏屏蔽的使用過核燃料風險。

Thick-walled containers to absorb radiation during transport of spent fuel have been used from the first such shipment in 1946 to the present time, during which several thousand shipments have been made. No container in normal use or involved in an accident has released any of its contents, nor has any increase in emitted radiation above levels allowed by the design ever been noted.

從 1964 年至現今，因厚壁容器可吸收輻射的特性，而開始運用該容器運送使用過燃料，在此期間已運送超過幾千次。沒有容器在正常使用下或發生事故時洩露其裝載物，也沒有散發出的輻射量超過設計的允許量。

Shipping containers (casks) for the transport of spent nuclear fuel are designed, fabricated, and operated under regulations prescribed by Title 10, Part 71, Code of Federal Regulations, "Packaging and Transportation of Radioactive Material." Such casks are strong, massive metallic cylinders that are designed to retain their contents under the most unlikely accident conditions. These casks are inherently safe containers for transporting large quantities of highly radioactive materials including spent nuclear fuel. Exposure of the public to radiation while the cask is in-transit is inconsequential

設計、製造與操作為運送使用過核燃料的運輸貨櫃或桶裝容器時，需依聯邦法規

10.71“放射性物質的包裝與運輸(Title 10, Part 71, Code of Federal Regulations, "Packaging and Transportation of Radioactive Material)”。這樣的桶裝容器，因具備大量金屬圓柱體，因此非常堅固，即使在最不可能的意外事故，內裝物仍不會外漏，這些桶裝容器具高度安全性可運送大量的高放射性物質包括核廢料。當此種容器在運送時，不會對社會大眾產生輻射危害。

The transportation section of the U.S. Department of Energy's "Environmental Impact Statement (EIS) for Yucca Mountain" considers the frequency that accidents can occur, their severity and their consequences, [3] both radiological and nonradiological. It concludes that in more than 99.99 percent of rail and truck accidents no cask contents would be released. Hypothetical accidents that could cause damage to a cask are very serious, very improbable, and expected to occur extremely infrequently. One such postulated accident could be expected to occur three times in each trillion truck accidents, a second such accident, three times in 100 trillion accidents. Confidence that casks will perform as designed arises from validated engineering analyses and from many tests using scale models and actual casks. That this confidence is not misplaced is borne out by the performance of casks in actual use. The record is perfect!

美國能源部運輸部門在"尤卡山環境影響報告書"中認為事故可能發生，且因輻射與非輻射的影響可能造成的嚴重程度與後果。它的結論是，在鐵路和卡車事故超過 99.99%非桶裝容器可能外洩。假設事故可能導致桶裝容器毀損，除非非常嚴重的事故，而且很不可思議，同時預計發生率非常低微。如此嚴重的事故發生率可能在數萬億件卡車事故中只有三次，之後再發生的機率可能在三百萬億件卡車事故裏只會發生三次。有如此之信心，因為桶裝容器之設計係源自驗證工程分析和使用許多測試比例模式與實際容器檢測。同時，桶裝容器也在實際運送中得到驗證，並留下完美的記錄。

"The safety record for spent fuel shipments in the U.S. and other industrialized nations is enviable. Of the thousands of shipments completed over the last 30 years, none has resulted in an identifiable injury through release of radioactive material."

在美國與其他先進工業化國家對使用過燃料的運送安全記錄是令人羨慕的，在過去 30 年間已完成數千次的貨物運輸，並且沒有導致放射性物質洩漏而產生明顯的危害。

A reliable transport system for the movement of spent nuclear fuel was recognized very early as an essential part of the process of making electricity from nuclear energy. Originally, it was expected that the spent fuel would be moved to a reprocessing plant for recovery of recyclable nuclear fuel materials and packaging of the radioactive waste materials for disposal. For a variety of reasons, large-scale commercial reprocessing of the spent fuel did not materialize in the United States. Instead a decision was made to treat the spent fuel as a waste for disposal. The Nuclear Waste Policy Act of 1982 (as amended) specifies that the federal government will take ownership of the spent fuel and assume responsibility for its disposal.

對於使用運燃料的運送系統，早已被認定是核能發電製造流程重要部份之一，且必須相對可靠。最初，使用過燃料預計被運送到後端處理廠後，重新回收核燃料物質與處置放射性廢料並丟棄。由於各種原因，在美國商業化大量再處理使用過燃料並實現。取而代之的是，把使用過燃料作為廢棄物進行處理。1982 年核廢料政策法案規定，聯邦政府對使用過燃料負責並承擔其處置的責任。

Users of nuclear-produced electricity pay for disposing of spent fuel by a surcharge of a tenth of a cent per kilowatt-hour, which is included in their electric bills.

核能電力用戶所需支付處理使用過燃料的費用為每使用每千瓦小時 0.1 分，已經包含在支付電費當中。

In July 2002 the Congress approved the site at Yucca Mountain in Nevada as the U.S. repository for disposal of high-level nuclear waste (which includes spent nuclear fuel). The U.S. Department of Energy is applying for site license from the U.S. Nuclear Regulatory Commission.

2002 年 7 月美國國會批准在位在內華達州的尤卡山作為美國貯儲庫，以便放置高放射性廢棄物，包括使用過核燃料。美國能源署申請由美國核子管理委員會的場地執照。

One concern is that adopting a central location in the western part of the country for spent fuel disposal will require shipping highly radioactive material across the country. According to some, the possible release of spent fuel in a transportation accident is an unacceptable risk.

其中值得關注的是在美國西部中心位置處理使用過燃料時，需將全國境內高放射性物質運送至該地。據了解，當運輸過程中發生事故時，因此可能使用過燃料發生洩漏的風險是令人無法接受。

This report provides information about the safety of the spent-fuel transportation system that has been in use for the past 40 years and under which several thousand spent-fuel shipments have been made with no release of any of the transported materials.

在該報告中提供了有關最近 40 年，幾千次使用過燃料的運送流程中沒有釋放任何運送材料的安全資訊。

Design Considerations.
設計考量

The chief factor that influences the design of the transport system is the need to protect the general public from exposure to the radiation emitted by the radioactive materials contained in the spent fuel. Thus, the shipping containers for spent fuel have to: Ensure that the spent fuel remains contained even under severe accident conditions.

影響運輸系統的主因是保護社會大眾避免暴露於因使用過燃料中所帶有的放射性物質所發出的輻射。因此，能裝載使用過燃料的容器，必須確保在容器在遭受嚴重事故情況下，裝載於容器內的物質不會外漏。

Ensure that radiation levels at the surface of the container are well below allowed limits during normal transport and under accident conditions. Ensure that the transported spent fuel cannot accidentally undergo a nuclear fission reaction.

From the beginning, it was believed that it was well within technical capabilities to design and fabricate a transport system that meets these performance requirements. It was also believed necessary to provide a regulatory framework to assure that the resulting system would consistently meet performance requirements.

同時，保證在正常的運輸和發生事故時，容器外表的輻射劑量遠低於允許值，並且確保運輸時不會意外發生核裂變反應。一開始，人們認為技術能力可完美設計與運作滿足性能規定的運輸流程；但也有人認為，有必要提供一個管理框架，以確保運作的系統將始終滿足性能規定。

Regulations Affecting Transportation Systems.

影響運輸流程的法規

The basic criteria for packages for shipping high-level nuclear materials and spent fuel originated in 1946 and were based on recommendations of the National Academy of Sciences. These recommendations served as guidance for manufacture of the early shipping casks for spent fuel and have been adopted by the International Atomic Energy Agency and by 53 nations.

運送與裝載高放射性核物質和使用過燃料的基本準則起源於 1946 年，且以美國國家科學院的決議案為基礎。這些決議案曾擔任早期運輸裝載使用過燃料桶裝容器的製造指南，並且被國際原子能機構和 53 個國家所採用。

Regulations were formalized based on the above criteria and in 1974 the United States Nuclear Regulatory Commission issued Title 10, Part 71, of the Code of Federal Regulations (10CFR71). This directive on the *Packaging and Transportation of Radioactive Material* is a detailed and comprehensive listing of requirements that must be met for safely shipping radioactive materials.

標準規定根據上述決議案與 1974 年美國核子管理委員會所發布之聯邦法律 10 CFR

71。該法條詳列並規範了對於安全運送射放性物質的包裝與運輸的規定。

A few of the 75 subjects addressed in 10CFR71 that pertain to spent fuel transport include (i) application procedure for package approval, (ii) the approval standards that a shipping package must meet for irradiated nuclear fuel transport, (iii) the tests that the package must meet, (iv) quality control procedures that apply, and (v) operational procedures to be followed in use of the shipping containers.

少數在 10 CFR 71 所涉及到使用過燃料運輸的 75 項科目裏，包括（i）許可的應用程序；（ii）必須符合進行輻照核燃料的運輸與包裝的許可標準;（iii）必須符合測試的包裝;（iv）質量控制的應用程序，以及（v）經營使用貨櫃運送應遵守的程序。

In conformance with this regulatory document, a typical spent-fuel container -- generally referred to as a cask -- is a 20- to100- ton cylinder consisting of concentric layers of steel alloy (for strength), a dense metal such as lead or uranium between the steel layers (for absorption of gamma radiation), a neutron shield wrapped around the cask, and a grid-work within the cask to hold the spent fuel. One end of the cask is fitted with a closure and seals capable of maintaining cask integrity under severe impact.

在符合規範文件中，基本的使用過燃料裝載容器，通常被稱為桶裝容器，是一個 20 到 100 噸重，由數層合金鋼所包裹而成的堅固圓桶型容器，高密度金屬如鉛或鈾層介於鋼圈裏，有助於伽瑪輻射的吸收，中子屏蔽層圍繞於圓桶內，與容器一同包覆住容器內使用過燃料。容器的一端裝有可密封的口蓋，能使容器在惡劣衝擊下，保持容器的完整性。

For example, casks for shipping spent fuel to Yucca Mountain are about 20 feet long and about six feet in diameter, depending on design.

例如，用於運輸使用過燃料至 Yucca 的桶裝容器，其尺寸約為 20 英尺長，直徑大約六英尺的直徑。

Performance Under Accident Conditions.

事故情況下的性能標準

A cask built in conformance with 10CFR71 has proven to be invulnerable to damage from the most serious accidents experienced on the nation's highways or railroads.。

符合 10 CFR 71 所建造的桶裝容器已被證明在經歷國家公路與鐵路最嚴重的損害事故中毫無毀損。

In December 1977 the Nuclear Regulatory Commission released its environmental statement on the transportation of radioactive material, NUREG-0170, which concluded that the risks associated with shipment in casks licensed to the standards of 10CFR71 are small.

1977 年 12 月美國核子管理委員會公佈放射性物質環保聲明- NUREG-0170，其結論是運輸依照 10 CFR 71 規範標準所製造桶裝容器，其風險是非常少的。

In February 1987 another comprehensive study was completed. [6] This study relied on historical highway and railroad accident information to define realistic accident scenarios. By applying engineering analyses to casks hypothetically involved in such accidents, realistic assessments of damage were made. The conclusions were that radiological risks are "...less than risks previously estimated in the NUREG-0170 document."

1987 年 2 月完成另一個全面的研究。本研究依據歷史上公路和鐵路事故訊息，以確定真實的事故情景，並藉由應用工程分析桶裝容器，假設事故中有此類容器，發表了實際損害評估報告。該報告結論是放射性風險為“......少於先前在 NUREG - 0170 文件中所評計的風險。”

In the mid-1970s Sandia National Laboratory conducted impact tests of shipping casks.[7] These tests simulated actual accidents. A highway-transported cask was mounted on its trailer and the trailer was attached to its tractor in the usual fashion. Similarly, a rail-transported cask was mounted on its special rail car and the car attached to a locomotive. These casks containing unirradiated nuclear fuel were subjected to a variety of tests including (i) being impelled by rocket motors at speeds of more than 60 miles per hour into a massive 688-ton concrete barrier backed by 1700 tons of dirt, and (ii) being struck broadside (truck transported cask) by a locomotive. These tests showed that the casks could be expected to retain their radioactive contents "... in extremely severe transportation accidents".

70 年代中期，美國桑迪亞國家實驗室進行運輸桶裝容器的撞擊試驗，試驗時模擬實際事故發生情況，一台拖車以通常掛附方式拖著桶裝容器在公路上運送，相同地，一輛動力火車拖帶著能裝載桶裝容器的專用載台。這些容器裝載著未輻照核燃料，以進行各種試驗，包括（i）遭受由火箭發動機推動速度超過每小時 60 英里，推撞至重量達到 688 噸的巨大水泥墩上，再緩衝至佈滿 1700 噸泥土堆中，以及（ii）拖車運輸桶裝容器由火車進行側面撞擊。這些試驗證明，在極其嚴重的交通意外當中，容器仍可維持放射性物質不至外漏。

Such accidents are very improbable. The 60-mile per hour highway impact was judged to occur with a probability of once every 70 years assuming seven million transport miles per year for spent fuel. Accidents corresponding to the other test scenarios are considered much less probable with average number of years between accidents ranging from 1,000 to 18,000 years.

這樣的交通事故是不太可能發生，每小時 60 英里的高速公路撞擊經判斷分析其發生率大約為，運輸使用過燃料時每年運輸里程為 700 萬英里，70 年才會發生一次。可能發生事故的機率，對應於其他測試場景，相較於發生率平均年數為 1,000 至 18,000 年間，則被認為發生可能性極其低微。

Even more important than the demonstration that these cask systems could perform as designed was the confirmation that scale models could be reliably used to predict full-scale performance and that the engineering analytical methods used were valid.

這些測試甚至超過這些桶裝系統依照能可靠地預測全面性能的比例模式與使用工程分析方法所規範的設計標準。

The impregnability of spent-fuel shipping casks is well accepted. For example in a Smithsonian article, the author states "Gasoline...is far and away the most dangerous cargo on the nation's highways. It would be possible to build gasoline trucks that are as well protected as those that haul nuclear fuel, but doing so, the carriers say, would mean paying much more for gas at the pump."

裝載使用過燃料的運送桶裝容器的堅固性已被大眾認可，例如在史密森文章中，作者指出，汽油......無疑地是國內高速公路上最危險的貨物，這將有可能構建能防護長途核燃料運輸之措施來防護汽油載運車輛，但運營商表示此種作法，將意味著使用者將付出更多汽油費用。“

Response to a Fire.
對付火災

Full-scale fire tests under extreme conditions disclosed that a cask could be exposed to twice the heat and three times the duration specified by the current regulations before cask degradation occurred. The response of the cask was well predicted analytically. In one test, the lead melted completely and some lead escaped, but no fuel was released. The probability of a railroad cask fire of this magnitude is estimated at once every 700 years.

極端條件下全面性火災試驗顯示，桶裝容器在退化前能夠暴露在兩倍於目前法規規定熱量和持續三倍以上的時間，容器的試驗反應可運用於預測分析上；在一次試驗中，幾乎所有鉛都融化但有一部分殘存，可是沒有任何裝載燃料外漏，對如此龐大的鐵路運送容器的火災發生概率,估計為每 700 年才可能發生一次。

Response to a Sabotage Attack.
應付蓄意破壞攻擊

A test to determine the amount of spent fuel that would be pulverized and become breathable if a cask were subjected to explosive penetration was undertaken in late 1981. The results of this experiment in which a 26-ton cask containing a single unirradiated fuel assembly was penetrated by a shaped charge explosive device, disclosed that very little of the fuel was converted to particles of a size breathable by humans.

1981 年底經由試驗來確定，裝載使用過燃料之桶裝容器遭受侵入性爆炸後，其中多少數

量將被粉沫化至可藉由呼吸而侵入體內，在試驗中以 26 噸重之桶裝容器內含單一非輻照燃料組件，由一個聚能孔彈爆炸裝置侵入，該試驗結果顯示只有非常少量的燃料，被粉沫化至可讓人類吸入體內。

Using the information garnered in this experiment, an analysis was made of the radiological consequences of a hypothetical accident in which a truck mounted cask containing spent fuel is assumed to undergo such an explosive attack in Manhattan, New York City. The results from nuclear causes were no early deaths (within weeks after exposure), no early fatality (deaths within a year after exposure), and possibly one cancer fatality later. (The study did not speculate on the number of deaths that might result from the explosion.) Certainly the nuclear effects were inconsequential as compared to homicides or vehicular accidents occurring in the same period in New York City.

運用該實驗中透露的資訊，假設運載使用過燃料車輛在紐約曼哈頓遭受爆炸攻擊，對放射性結果進行分析。結果顯示沒有因遭受核子

曝射後一個週內死亡，或在遭受曝射後一年內死亡，以及在往後可能因癌症而死亡；這項研究並沒有推測因爆炸可能導致死亡的數目。當然，此種事故相較於紐約市同一時期所發生的兇殺或車輛事故，所導致的傷亡人數是微不足道的。

Conclusion
結論

A combination of good regulatory standards, good engineering design, quality controlled fabrication and inspection processes, validated performance of scale-model and full scale casks under a variety of test conditions provide a high degree of confidence that containers used for the shipment of spent nuclear fuel will do their job safely, both in normal use and in the event of very serious accidents.

結合良好的控管標準、工程設計、製造品質以及檢驗流程，經由量化模式與全面性認證性能，以及在各種測試條件下加以確認，無論是在正常使用和非常嚴重的事故下，桶裝容器

用於裝運核廢料，在工作安全上將提供高度的可靠性。

Backup Information

其他訊息

Hypothetical Accident Conditions from 10CFR71.73

假設 10 CFR 71.73 情況下的事故

A cask for shipment of spent fuel must be able to survive the following tests:

運送使用過燃料的桶裝容器必須在下列測試中完整無損：

A drop through 30 feet onto an **unyielding** surface. ("Unyielding" is the main point here, as this ensures that the kinetic energy of the drop is all applied to the cask. We all know that a light bulb will usually survive a fall onto a carpet, but will not live through impact with a concrete floor.) In practice, in addition to the collapsible structural components of the cask system, engineered collapsible "impact limiters" are attached to the casks to provide a "yielding" surface in the event of accident.

自 30 英尺高度自由落體至堅硬表面；堅硬表面是非常重要的，因為落體動能都適用於桶裝容器，我們都知道，當燈泡落到地毯上通常不會破裂，但與混凝土地撞擊時就會破裂；實際上，在桶裝容器結構上均有可折疊構件，在可折疊構件上設計“撞擊緩衝器”，在這樣事故情況下對容器而言，可提供一個“柔軟”的撞擊介面。

Impact by an 1,100-pound mass falling through 30 feet.

由重達 1100 磅物塊至 30 呎高度自由落下的衝擊。

Fall of the cask from a height of 40 inches onto a steel post 6 inches in diameter and 8 inches long.

桶裝容器從 40 吋高度落到直徑 6 吋長 8 吋的鐵柱上。

Exposure to an engulfing fire at 1,475 degrees Fahrenheit for 30 minutes.

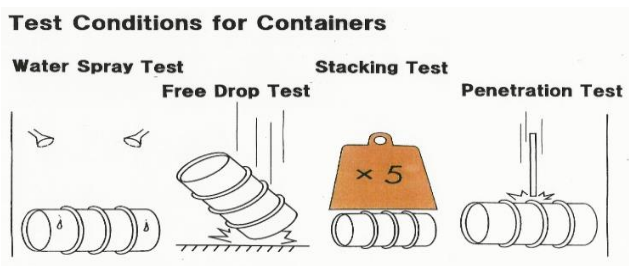
暴露在華氏 1,475 度的大火中持續 30 分鐘。

Immersion under three feet of water. (An undamaged specimen of the cask must not leak when immersed to a depth of 50 feet -- or a pressure equivalent of 21.7 pounds per square inch.)

在浸泡水面下三呎，未損壞的試樣桶裝容器在下沈至 50 呎深度或壓力相當於每平方英寸 21.7 磅時，不能有任何的洩密情形產生。

Orientation of the cask in each test is to be such as to assure maximum damage. The impact tests are to be applied successively, followed by the fire and water tests. Thus the cask must maintain its integrity through all of these tests.

每次桶裝容器的測試的方針，是確保容器遭受最大損害，在衝擊試驗完緊隨其後由火場及浸水試驗相繼應用。因此，桶裝容器在經歷這些測試後，必須保持其完整性。



Spent Nuclear Fuel
使用過的核燃料

Spent nuclear fuel looks just like it did when it was loaded into the reactor. Within the fuel rods there is a change in the atomic species due to fission of uranium and plutonium in the reactor and radioactive decay after removal from the reactor. There is a minuscule loss of weight because in the fission process some mass is converted into energy (heat).

當核燃料被裝入反應爐內燃料就開始使用了，因燃料棒內在反應爐內原子產生鈽與鈾的分裂，在取出後則會放射性衰退；另外，因為在分裂過程中分子被轉換成熱能，造成質量微小損失。

Typically, nuclear fuel consists of 1/2 -inch diameter by 1/2 -inch long ceramic uranium dioxide pellets stacked in 13-foot long tubes of a zirconium alloy. From 63 to 264 of these fuel rods, depending on the particular fuel design, are mounted in metal fixtures. These fuel-rod aggregations are called fuel assemblies.

通常，核燃料是由直徑與長度各為 1/2 吋的瓷化二氧化鈾丸堆疊在由鋯合金製成長為 13 呎的管子裏，燃料棒數量由 63 到 264 支安裝在金屬夾具上，燃料棒數量取決於特定燃料設計，這些燃料棒聚合後被稱為燃料組。

A large number of fuel assemblies -- containing a total of 120 to 140 tons of uranium -- are grouped in the "core" of the reactor. When the reactor is operating, fission and radioactive decay produce heat mostly within the fuel rods. This heat is transferred to water pumped through the fuel assemblies and the water is directly or indirectly converted to steam. The steam powers turbine-generators that produce electricity.

含有總共 120 至 140 噸鈾的大型燃料組，被群聚在反應爐的核心內。當反應爐運轉時，燃料棒會產生分裂與放射性衰變並產生大量熱能。這些熱量被傳遞到泵送通過燃料組件的水，水則被直接或間接地轉化為蒸汽，帶動蒸汽動力渦輪發電機轉動產生電能。

This is the same way that electricity is usually generated except that the heat is provided by a nuclear reaction rather than by a chemical combustion process such as the burning of coal, gas, oil, or other fuel. A significant difference is that in the nuclear powered system there are almost no gases -- greenhouse or otherwise -- emitted.

與其他熱能發電相同方式，只是產生電力所需之熱能是由核反應所供應，而不是通過化學燃燒過程提供，如煤、天然氣、石油或其他燃料的燃燒過程所產生。顯著不同的是，核動力系統中幾乎沒有溫室或其他氣體排放。

The fuel rods remain in the reactor typically for three or four years, in 600-plus degree Fahrenheit water and at a pressure exceeding 1,000 pounds per square inch. In some instances, reactors have run continuously for over a year at essentially full power -- a quite remarkable technical feat. The fuel rods survive this harsh environment very well.

燃料棒放置在反應爐內一般為三到四年，在華氏 600 多度的重水中，壓力超過每平

方英寸一千磅，某些情況下，反應爐已連續在滿載功率下運行一年多，燃料棒仍狀態良好。

About every 18 to 24 months, one-fourth to one-third of the fuel rods are no longer suitable for continued use in the reactor. They become "used" or "spent" fuel and are removed and replaced by fresh fuel.

大約每 18 到 24 個月，四分之一至三分之一的燃料棒不再適合於在反應爐中繼續使用，這些燃料棒則成為使用過或廢棄的燃料，其將會將被移除，並置入新燃料棒。

Upon removal from the reactor, the spent fuel is stored under water in a basin to allow the short-lived radionuclides to decay to more-stable isotopes and to reduce the heat emitted by radioactive decay.

從反應爐抽取後，廢棄燃料棒將存儲在爐下水槽中，使衰退期較短的放射性核元素衰變到更穩定的同位素，並減少由放射性衰變產生的熱能。

When a nuclear power plant is shut down, the rate of heat production immediately drops by a factor of 16 to about 6% of what it was when the fission process was ongoing. An hour later, it is down by a factor of 100 to about 1%. After a month, the power reduction factor is about 1,000 (0.1%). After a year it is about 5,000 (0.02%) and after 5 years about 30,000 (0.003%).

當核電廠關閉後，熱量產生率立即下降至功率降低係數 16，約由開始裂解時熱能的 6%。一小時後，下降至功率降低係數 100(1%)。一個月後，功率降低係數約為 1000（0.1%）。一年後，係數約 5,000（0.02%）；5 年後係數約為 30,000（0.003%）。

Freshly discharged spent fuel is stored in deep pools at the reactor covered by at least nine feet of water. The water provides both shielding from the radiation and removal of heat from the radioactive decay.

剛抽離的使用過燃料儲存在反應爐下至少九英尺深的深水裏，水既可提供輻射屏蔽同時又可去除放射性衰變所產生的熱能。

After about five years of water storage the heat output of the spent fuel is reduced to the extent that it can be stored in massive concrete containers that are air cooled by convection. According to federal regulation, the spent fuel is considered to be High Level Nuclear Waste.。

經過大約五年儲水期間，使用過燃料的熱能輸出減少到，可以被存儲在大型混凝土容器內，同時保持空氣通過對流即可冷卻容器。根據聯邦法律，使用過燃料被認定為是高放射性核廢物。

Member of the Center for Reactor Information (CFRI). The author has had personal managerial experience with the safe transportation of spent nuclear fuel in over 500 truck shipments and over 100 railcar-shipments of spent fuel with no accidents and no consequences to the public. He believes that the existing procedure for shipping spent fuel is a well established and safe procedure that has proven more than adequate over the test of time.

反應爐資訊中心（CFRI）的成員，曾有超過 500 次卡車以及超過 100 次鐵道運輸核廢料，但沒發生任何意外與影響到市民的安全運輸個人經驗。他認為，現有的運送使用過燃的作業程序是一個完善且安全的流程，同時已經通過時間的考驗而得到證明。

Nuclear fuel is the uranium material that undergoes a nuclear reaction in a nuclear reactor to produce heat and steam for the production of electricity. Spent nuclear fuel is, for a variety of reasons, no longer useful to sustain the nuclear heat-generating reaction. The spent fuel can be thought of as the ashes of the nuclear reaction. Spent fuel is exceedingly radioactive, is inherently dangerous, and must be handled with great caution.

核燃料是由鈾元素組成，鈾元素在核反應爐中經過核子反應，同時產生熱能與蒸汽，帶動發電機產生電能；基於各種原因核廢料不再具有維持核發熱反應的使用性，核廢料可以被認為是核反應的殘留物，但核廢料極具放射性，本質上是危險的，必須非常謹慎處理。

Spent Fuel Shipping to Yucca Mountain
運送使用過燃料至尤卡山

Because of the incredible efficiency of the atom as a power source, very little spent fuel is produced each year. A typical modern nuclear reactor that operates at a 1,000 megawatt electrical power level will use 20 to 30 metric tons of uranium per year[14] and, therefore produce, at the most, 30 tons of spent fuel. This 30 tons of fuel will make about 8,000,000,000 kilowatt-hours (kwh) of electricity.

因為使用原子作為動力源其效能非常可觀，同時每所產生的核廢料數量非常少。現代傳統式核子反應爐在 1000 兆瓦的電功率產能下，每年將使用 20 至 30 公噸的鈾燃料，並因此產生至多 30 公噸核廢料。30 公噸鈾燃料可產生約 80 億瓩時的電力。

An annual production of spent fuel would require less than three rail shipments to Yucca Mountain per year, each shipment consisting of a special train of three rail cars, each car containing one cask.

每年產生的核廢料經由鐵路運輸到尤卡山只需不到三次，每次運送由三節載運車箱，每節車箱裝載著一個桶裝容器。

For perspective, to generate this same amount of electricity from coal requires burning about 3,000,000 tons. Transporting this much coal, each year, takes over 300 train loads, each train consisting of over 100 rail cars, each car containing 100 tons of coal -- in all 30,000 car loads.

換個角度看，電產生相同電力需要約 300 萬噸的煤，要運送這麼多的煤，每年需要由 300 輛列車載運，每輛列車有 100 節車廂，每節車廂裝有 100 公噸煤。

In 1999 there were about 40,000 tons of spent fuel stored at reactors and in away-from-reactor storage around the country and another 20,000 tons would be produced before Yucca Mountain is ready to receive any spent fuel.

1999 年，約有 4 萬噸使用過燃料儲存在核電廠內與全國各地核電廠外的貯儲場區，在尤

卡山貯儲場完成前將另外產生約 2 萬噸的核廢料。

How quickly the spent fuel needs to be removed from the reactors and transported to Yucca Mountain will determine the rate at which the spent fuel will need to be shipped and will require answering a number of questions. The logistics of the spent fuel shipping system, including availability of casks, turn-around time, etc., will determine the most efficient method of operation.

如何迅速地將使用過燃料從反應爐內移除並運送至尤卡山，將取決於運送使用過燃料的物流，其中包括能使用的桶裝容器與運送工具的運行時間等，以決定最有效的運作流程。

Answering these questions is simply a typical business problem -- one that requires good interfacing between the Yucca Mountain disposal site, the shippers, the railroad, and regulators. Though the transportation process is not simple, it is a routine commercial activity, and many experts will pay close attention in the planning and execution.

此外，亦包括尤卡山處置場、運送人、鐵路交通，以及監管機構之間的良好連繫。雖然運輸過程並不簡單，亦是常規的商業活動，許多專家將密切關注運送流程的規劃與執行。

Effects of Sabotage Explosive Assault
蓄意爆炸破壞襲擊的影響

The risks associated with a sabotage assault on a spent fuel shipment depend on how much radioactive material will be released from the cask as a respirable aerosol. In the earliest regulations there was no empirical information available, so risks were based on speculative scientifically based estimates. A Sandia study, SAND 77-1927 to estimate the radiological consequence of a sabotage event, assumed that 0.07 percent of the spent fuel in the cask could be converted to a respirable form. This value was acknowledged to be very conservative and fraught with uncertainty.

運送使用過燃料在遭受破壞攻擊時的相關風險，取決於有多少放射性物質會從桶裝容器內洩漏，並粉化為人體可吸入之粉沫數量；在最早的法規中並沒有具經驗性之資料可供參考，所以風險是基於純理論科學依據概估量而得。在聖地亞研究中，估算出在破壞事件中洩漏放射性的後果，假定在桶裝容器中 0.07% 的使用過燃料被粉化成可吸入粉沫，該值被認為非常保守並充滿不確定性。

Based on the potential risk that this study suggested, the NRC imposed a number of temporary rules to reduce the chance that such a sabotage event could occur.

基於這項研究所發表的潛在風險，核能管理委員會追加一些臨時性的規則，以減少可能發生此類破壞事件的機會。

Both the NRC and the Department of Energy, realizing that realistic data were needed as a basis for realistic regulations, sponsored experimental programs to pin down the question of how much spent fuel subject to a violent explosive attack would be converted to a respirable aerosol.

核能管理委員會與能源部，體認到現行法規需要實際數據為基礎，在實驗報告中，可確定有多少使用過燃料在遭受猛烈的爆炸攻擊後，被粉化為可吸入粉沫的問題。

Battelle Memorial Institute conducted experiments using actual spent fuel. Sandia National Laboratory conducted a full-scale program using an obsolete shipping cask and unirradiated fuel. The results of these programs complemented each other and it was learned that the actual formation of respirable fraction was very much less than had been estimated in the previous study.

巴特爾紀念研究所運用實際使用過燃料進行實驗；桑迪亞國家實驗室則使用一個淘汰的運送桶裝容器與未輻照燃料進行全面性實驗。這些實驗方案的研究結果相互補充，並指出被粉化成可吸入粉沫之實際數量遠小於先前研究的估計值。

In Sandia's full-scale test[6] the amount of material in the respirable range was found to be only about 1/10 of an ounce of uranium dioxide from

220 pounds damaged in the spent fuel.. This is about 0.0006 percent of the fuel or less than 1/100 of that assumed in the earlier study.

在桑迪亞的全面性試驗中，發現被粉化為可吸入粉沫量，由 220 磅遭受攻擊的使用過燃料，約只有十分之一盎司的二氧化鈾被粉化，粉化量約佔燃料的 0.0006%並且遠小於早期研究中假定量的百分之一。

This full-scale test confirmed that the effect of the explosive charge was to shatter the material affected rather than to pulverize it. This knowledge is also useful in planning for clean-up after such an event should it occur.

這種全面性試驗證實，爆炸的作用是破壞物質，而非粉化物質；這方面的知識提供規劃爆炸事件清理善後時非常有用。

In applying this new experimental data to a radiological consequences analysis, it was learned that if such a sabotage event were to take place in Manhattan, New York City, it would result in no early fatality nor morbidity -- apart from the effects of the explosion -- and no more than one later cancer fatality.

運用新的實驗數據為放射性後果進行分析，分析指出如果此種爆炸破壞事件發生在紐約市曼哈頓，並不會導致早期病死率與發病，除了因爆炸而死傷外，也不會造成癌症致死。

Actual Cask Accident Experience
桶裝容器實際意外經驗

The safety record for spent fuel shipments in the U.S. and other industrialized countries is enviable. Of the thousands of shipments completed over the last 30 years, none has resulted in an identifiable injury through release of radioactive material.

使用過燃料的運輸量在美國與其他工業化國家的安全記錄是令人羡慕的，過去 30 年間已運送了成千上萬的運貨量，其中並沒有導致因放射性物質洩漏所造成的傷害。

He goes on to say that in the period from 1979 through 1995, 356 metric tons of spent fuel were shipped in 1,168 highway shipments and 979 metric tons in 138 rail shipments.

從 1979 年到 1995 年期間，356 噸使用過燃料經由 1,168 次公路運送，138 列次的鐵道運輸，則運送了 979 噸。

During 1971 to 1995 eight accidents involving casks took place, with no release of radioactive material in any of them. In four of these accidents, the casks were loaded with HLW.

在 1971 年至 1995 年間涉及桶裝容器意外事故共發生八件，在事故中並沒有任何放射性物質洩漏；其中有四件意外，桶裝容器內均裝載著高放射性廢棄物。

- In one accident the truck left the road and the cask was thrown from the trailer. The cask was slightly damaged but was repaired. The driver was killed.

  其中一個意外是卡車駛離公路容器被摔離車體，容器只是輕微受損可被修復，但司機則事故死亡。

- In two incidents the truck/trailers failed. The casks were undamaged.

另兩件事件是的載具故障，但容器並無毀損。

- In the fourth accident a train carrying two casks of Three-Mile Island core debris collided with a car. The casks were undamaged.

第四起事故是火車載運兩個桶裝容器，容器內裝填三哩島的核碎片，與一輛汽車相撞，事故發生後桶裝容器仍是完好。

Environmental Impact Statement
環境影響報告書

"The purpose of the environmental impact statement (EIS) is to provide information on potential environmental impacts that could result from a Proposed Action to construct, operate and monitor, and eventually close, a geologic repository for the disposal of spent nuclear fuel..."

環境影響報告書的目的是提供對環境造成潛在影響的資訊，其中包括建造、操作與監控及最終關閉，處置核廢料的地質資料庫等的擬議提法。

The EIS analysis considered the impact of 10,700 rail shipments over a 24-year period using 21 rail-accident cases that ranged from very common accidents to those so very unlikely as to be almost impossible -- "the maximum reasonably foreseeable accident." Latent cancer fatalities from the latter improbable event were estimated to be five for the rail scenario. For this same kind of accident three traffic fatalities were calculated. Consequences from various collisions, fires, and combinations of collision and fire were examined.

環境影響報告書的分析認為在 24 年間達 10,700 次鐵道運輸，只造成 21 起軌道事故案例，在一般事故理念中，其發生率幾乎很小。在事故中最大合理預期的死亡數為，在鐵路運道中因癌症死亡人數估計為五人；藉此可推算出因道路交通事故而導致癌症致死人數則為三人，其推論是由碰撞、火災與結合碰撞及火災等試驗而得。

The consequences of an accidental crash of a large jet aircraft into a cask were also calculated. The cask would not be penetrated, but failure of the cask seals would result in a fraction of one latent cancer fatality.

其中還計算桶裝容器被一架大型噴射機的意外碰所造成的後果；結果顯示桶裝容器不會被穿透，但容器密封結構失效將會導致一小部份民眾因潛在癌症而死亡。

Existing Spent Fuel Shipment Procedure
現行使用過燃料運送程序

"Internationally, more fuel has already been shipped and successfully transported than is scheduled to be shipped to Yucca Mountain. Following is an abbreviated description of the various activities that are currently undertaken in the shipment of spent nuclear fuel. This listing may not include every item, but should provide a reasonable understanding of the process.

國際間更多的燃料已成功運送到目的地，其數量比原定運往尤卡山的還多。以下是目前運用在核廢料運送的各種流程簡化描述；本文並不包括詳述每一細項，但是提供合宜的說明。

For simplicity's sake this description deals only with rail shipment, since this is the most likely shipment mode to Yucca Mountain. Currently, rail shipments are made by special train and it is assumed that that policy will continue. Advance arrangements are made to assure a compatible schedule between the shipper of the spent fuel (the utility), the receiver of the spent fuel, the provider of the shipping casks, and the railroad.

為了簡單起見，這部分只涉及鐵道運輸，因為這是運送至尤卡山最可行的運輸模式。目前，鐵道運輸是由專責運送的列車載運，而且該政策將會持續。為確保燃料運送順暢，托運人、收貨人、載具供應商以及鐵道車班等所有相關部門的時間表均會提前安排。

Preliminary

序言

A schedule is made for notification of regulatory and other organizations as may be required. The route is established and whether it will require armed guards and state notification.

時間表可作為管控申報書以及通報其他相關單位的依據，運送路線規劃以及是否需要武裝警戒與狀況是須要通報的

Shipping site activities

運送場地的流程

Standard Operating Procedures are prepared and approved. Site personnel are trained in loading the cask. Equipment is identified and checked out. The empty cask is received. Measurements are made on the empty cask to assure shipping regulations have been complied with.

標準作業程序已備妥並得到許可；現場工作人員均已接受過裝載桶裝容器之訓練，設備已認可並檢查完畢；空容器收受完後；測量容器是否符合運送法規規定。

The cask's personnel barrier is removed, the impact limiter is removed, and the cask moved to the preparation area. It may require cleaning. The nuts or bolts that hold the cask head on are removed. The cask is moved to the transfer area of the spent fuel storage pool and the head removed to its temporary storage spot. Spacers, if needed to adjust for various fuel assembly lengths, are installed. The spent fuel assemblies are transferred from their storage positions to the grid in the shipping cask. All movements of the spent fuel under water must maintain at least nine feet of water over the fuel.

容器的保護屏壁被移除時，衝擊緩衝器也會一併移除，此時再將容器移到裝貨準備區，以便清洗。卸下固定容器頂蓋的螺栓；容器移動到使用過燃料存儲池的運送區而頂蓋則移至臨時存儲站。如因裝載各類燃料組件的長度不同而需要調整時，則需安裝間隔物。使用過燃料組從儲放地點轉送到桶裝容器隔間內。裝載使用過燃料的流程，均需在至少九英尺深的水池內進行。

Fuel identification numbers are recorded for accountability purposes. The cask head is replaced and the cask removed from the storage pool.

The cask is drained of residual water. The cask head is fastened down and the cask leak-tested.

Records that all operations were done according to the appropriate Standard Operating Procedures are verified.

記錄燃料識別碼以備查尋，重新裝置頂蓋桶裝容器則自儲存池內轉運出。容器排出殘留水份，固定頂蓋並對容器進行洩漏測試。所有操作都根據相應的標準操作程序進行記錄並且驗證。

The cask is scrupulously cleaned to assure that surface contamination is well below regulatory limits. The loaded cask is returned to its rail car, the personnel barrier is re-installed and final measurements made to determine radiation levels outside the cask. Shipping papers are provided the carrier. Final confirmation is made that all transportation safety requirements have been met. The cask is tendered to the railroad, which transmits it to its destination.

桶裝容器需清理整潔，以保證表面污染源低於法規限定值。裝填完畢的桶裝容器再裝載至運送列車上，重新裝置保護屏壁，再進行最終測量，以確定桶裝容器外層輻射劑量。運輸

文件放置在運輸列車上，最後再確認是否符合運輸安全所有要求，桶裝容器設計成使用鐵道運輸，並將貨物運送至其目的地.