GE 1712
能源核電與輻射

核能發電簡史與核能發電原理

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物理界對物質結構的探討與重大發現

~400 BC: Democritus; 提出 原子(atom) 的名稱

1803: *John Dalton* --- *Atomic Hypothesis*; 物質是由不可再分割之原子所構成

1876: 陰極射線管 (Cathode Ray Tube) 的發明; 氣體放電現象

1887: *Hertz*; 光電效應 (Photoelectric Effect); 紫外線撞擊金屬版可產生電流

1897: *Thomson*; 發現電子, 原子內含有電子

原子為電中性. 原子內含有電子(帶負電荷)及正電荷

原子內正電荷與負電荷的分佈?

1898: *Thomson*; 認為原子內的正電荷呈球型分佈, 而電子均勻散佈於球體內

1895: *Roentgen*; X-ray的發現, 高頻電磁波 (electromagnetic wave)

1896 ~ 1898: *Becquerel* & *Curie*; 發現輻射 (radiation) 及
放射性核種 (radioactive element),
阿爾發粒子(Alpha Particle), 貝他粒子(Beta Particle),
加馬射線 (Gamma Ray)

1902: *Rutherford*; 提出自然放射性衰變所釋出的能量為
化學反應釋出能量的百萬倍的看法

1905: *Einstein*; 提出質量與能量間的關係式

$$\Delta E = \Delta M C^2$$

1911: *Rutherford*; 利用阿爾發粒子撞擊金箔, 發現原子核 .

1913: *Bohr*; 提出氫原子 (hydrogen atom) 之量化理論模型說明
氫原子原子光譜

1919: *Rutherford*; 證明核反應可以發生

$$He_2^4 + N_7^{14} \Rightarrow O_8^{17} + H_1^1$$

1930: *Bothe & Becker*; 發現下列兩個核反應

$$He_2^4 + Be_4^9 \Rightarrow C_6^{12} + n_0^1$$

$$He_2^4 + B_5^{11} \Rightarrow N_7^{15} + n_0^1$$

不帶電粒子,可穿透極厚的材料

1932: *Irene Joliot & Frederic Joliot*; placing a layer of hydrogenous material in front of the Geiger counter causing the counting rate to increase → ejection of Proton from the hydrogenous layer;

1932: Chadwick; 認為上述反應釋出之不帶電粒子

1935: Fermi; 利用中子撞擊鈾靶可產生超鈾元素 “transuranic” elements ； 鈾元素是自然界存在之最重的核種

Leo Szilard 將利用核連鎖反應產生大量能量的觀念申請專利
However, the concepts was not based on Uranium.

1938: Otto Hahn & Fritz Strassmann: 證明所謂的超鈾元素中包含鋇(Barium), 一個較鈾核為輕的核種.
--- 中子可以造成鈾原子核的解體

Metiner and Frisch 以核分裂 (Nuclear Fission) 解釋 Hahn-Strassmann 所觀察到的現象

實驗可以證明核分裂反應中可再釋出中子

$$U_{92}^{235} + n_0^1 \Rightarrow Ba_{56}^{139} + Kr_{36}^{84} + 3n_0^1$$

fission yield

連鎖核分裂反應 (Nuclear Chain Reactions), 可釋放出大量能量.

~ 200 MeV / Fission = 3.20 x 10^{-11} W – sec
1 g of U 相當於 960 kW – day energy
3 噸的煤 或 600 加崙的汽油
1 kg of U is equivalent of 16,000 tons of TNT

自然界的鈾有兩種同位素; U-235 (0.72%), U-238 (99.28)
只有 U-235 可維持連鎖核分裂反應

1939: Heisenberg; 提出發展 “原子彈(Atomic Bomb)” 的可能性

Szilard, Wigner, & Teller Persuaded Einstein to wrote a letter to President Roosevelt about possible German development of extremely powerful bombs of new type.
Suggested: obtained supply of Uranium, speed up the experiment work, getting cooperation of industrial

1941: Seaborg; 發現鈽元素 (Plutonium)

$$U_{92}^{238} + n_0^1 \Rightarrow U_{92}^{239} \Rightarrow Np_{93}^{239} + \beta_{-1}^0$$
$$\Rightarrow Pu_{94}^{239} + \beta_{-1}^0$$

可裂物質(Fissile): U-235, Pu-239, U-233
可孕物質(Fertile): U-238, Th-232

核反應(Nuclear reactions) 與
反應截面 (cross section) --反應發生機率

反應截面與核種, 反應類別, 中子能量(中子與核種之相對速度）有關

1942: August 13th , established “Manhattan Engineer District”,
Develop an Atomic Bomb as soon as humanly possible.
Manhattan Project: 1942~1945, 2 billion US$

曼哈頓計劃主要工作項目:

1. 發展程序以生產製造原子彈所須之濃縮鈾與鈽

同位素分離: 氣體擴散 (gas diffusion)-Columbia University,
雷射同位素分離法 (UC Berkeley)
氣體擴散廠 (Oak Ridge Laboratory)

設計可以產生大量中子之裝置,將 U-238 轉換為Pu-239
裝置稱為反應器 (reactor)

反應器內發生穩定而持續之連鎖核分裂反應

$$K_{eff} = \frac{\text{number of neutrons of } (N+1)\text{th Generation}}{\text{number of neutrons of } (N)\text{th Generation}}$$

K_{eff}=1 臨界(critical), K_{eff},<1 次臨界 (subcritical),
K_{eff},>1 超臨界 (super critical)

臨界試指反應器內產生的中子與消失的中子數相等

產生：核分裂；　消失：被吸收，由邊界逃逸

$$K_{eff} = K_{\infty} P_{non-leakage}$$

K_{∞} : determined by material properties

$P_{non-laekage}$: size and material properties dependent

反應器內吸收中子之物質:燃料, 緩和劑(減速劑), 結構材料, 冷卻劑, 控制材料

中子自反應器逃脫機率與反應器大小成反比- 臨界質量 (critical mass)

當緩和劑的質量數越大時, 臨界的尺寸(臨界質量)越大

1942 Dec. 2nd: the first controlled nuclear fission reaction took place at West Stands of Stagger Field on the University Chicago campus.

Chicago Pile - 1; 燃料: U and UO_2 (40 tons);
緩和劑: Graphite (385 tons)
尺寸: 9 m x 9.5 m x 6m; 功率: 0.5 W to 200 W

Scram (出去, 走開): Safety Control Rod Axe Man

Experiment Pile (University of Chicago, Enrico Fermi)
鈽生產反應器 (Hanford –B Reactor)
鈾與鈽的化工分離程序 (Oak Ridge Laboratory)

Handford Reactors: 鈽生產; 燃料: UO_2; 緩和劑: Graphite;
冷卻劑: 水

曼哈頓計劃主要工作項目:
2 設計與製造核子武器(Atomic Weapon);
Los Alamos Laboratory, Robert J. Oppenheimer
計算臨界質量, 設計引爆裝置(detonation of the bomb)

1945 July 16th: Trinity Test; 10,000 tons of TNT

1945 August 6th: Hiroshima, “Little Boy”, U Bomb

1945 August 9th: Nagasaki, “Fat Man”, Pu Bomb

第二次世界大戰結束　各類型反應器的發展

1945 Sep. 5th: 一組國際科學家於 Chalk River Canada 建造一小型之
重水反應器; 燃料: 天然金屬鈾; 緩和劑: 重水

1946 Dec. 31th: 美國成立原子能委員會(Atomic Energy Commission)
將核能資訊與知識視為國家機密

1951:美國原子能委員會邀請美國工業界加入發展 鈽生產及發電
雙重功能反應器之設計工作

1951 Dec. 10th: the first nuclear electricity was generated by the
Experimental Breeder Reactor-I at Idaho USA
孳生反應器(快中子)

1953 May: The Submarine Test Reactor (STR) sustained production
of large amount of mechanical energy for several days.
STR: 壓水式反應器Pressurized Water Reactor (PWR);
美國西屋公司在壓水式反應器的發展中扮演著重要的角色

1953 July: 第一座沸水式反應器 Boiling Water Reactor (BWR)
– Borax-1 開始運轉

1953:美國艾森豪總統於聯合國提出核能和平用途 “Atomic for Peac
計畫; 開啟了核能和平應用與發展的大門

1954 June 27th: 世界第一座核能電廠 (5 MWe) 於前蘇聯Obninsk
開始商業運轉 (石墨水冷反應器 (RBMK))

核分裂現象發現後 15 年

1954 September: 世界第一艘核子潛艇鸚鵡螺號 (Nautilus) 下水

美國1997年擁有 84 艘核子動力潛艇,9 核子動力艘航空母艦,
2 艘核子動力導彈巡洋艦,113 艘核子動力船艦已除役

1955: BORAX III 反應器 (奇異公司設計之沸水式反應器)
產生足夠 Arco, Idaho USA 小鎮使用之電力

1956 October: 世界第二座核能電廠 (50 MWe) 於英國 Calder Hall
開始商業運轉 (石墨器冷反應器 (GCR))

1957 July: 聯合國成立國際原子能總署 (International Atomic
Energy Agency (IAEA)) 發展與管制核能
禁止核武器擴散公約, Nuclear Nonproliferation Treaty (NPT)

1957: 世界第一個核能電廠事故於英國 Windscale 發生;
氣冷, 石墨緩和, 鈽生產用反應器
石墨於事故中起火燃燒, 造成大量放射性物質外釋

1957 December: Shippingport 核能電廠(60 MWe)於美國賓州
開始商業運轉; 世界第一座商用壓水式反應器 (PWR)

1957 December: Dresden-I 核能電廠(170 Mwe)於美國伊利諾州;
開始商業運轉; 世界第一座商用沸水式反應器 (BWR)

1962: 世界第一座重水式反應器電廠於加拿大 Rolphton, Ontario
開始商業運轉

重水式反應器CANDU; 燃料: 天然鈾,
緩和劑:重水 (heavy water), 冷卻劑: 普通水(ordinary water)

1964: 前蘇聯第一座石墨水冷反應器 (RBMK reactor) 於 Beloyarsk
開始商業運轉

石墨水冷反應器; 燃料: 低度濃縮鈾;
緩和劑:石墨, 冷卻劑: 普通水(ordinary water) – 沸水

1973: 第一次石油危機

1975: 美國原子能委員會發佈反應器安全研究報告
(Reactor Safety Study, RSS, WASH-1400)

- 核電廠使用之反應器無法達到絕對安全的要求,
- 核電廠發生嚴重事故的機率極低
- 核電廠即使發生嚴重是故亦不一定造成毀滅性的災變
- 核電廠附近居民因核電廠嚴重事故而喪失生命的機會與被殞石打死的機會相當

1979 March 28th: 美國賓州三浬島 (Three Mile Island ,TMI)
核電廠發生爐心熔毀事故
B&W 設計之壓水式反應器; 爐心於事故中嚴重熔毀,
圍阻體保持完整成功的防止放射性物質大量的外釋至環境
極少量的放射性物質外釋, 州政府疏散電廠附近部分民眾
核工業界認為不可能發生之爐心熔毀事故終究發生了
但並未造成毀滅性的災難
核工業界,電力公司,法規管制單位開始檢討核電廠安全措施
並進行自幅度之改善

TMI事故是核能工業的最大危機，但也是最大的轉機

1979: 第二次石油危機

1986 April 26th: 前蘇聯(現為烏克蘭共和國)發生Chernobyl accident;
石墨水冷反應器 (RBMK); 反應器於功率大幅驟生事故解體,
石墨於事故中起火燃燒, 溫度高達 5000 度
50 萬居里之放射性物質外釋, 須疏散大區域之居民
32 個電廠工作人員及救火對原因輻射傷害喪生

核能發電現況

2002 年底全世界有 441 部核能機組,總裝置容量為 359,000 MWe
總發電量為 2,574 TWh

2001 年底全世界有 438 部核能機組,總裝置容量為 355,000 MWe
總發電量為 2,544 TWh

2001 世界上使用核能發電國家

核能發電具有 准自產能源 的特質, 故能源依賴進口的國家
均維持一定之核能發電比例

部分國家仍持續興建核能電廠

世界個核能使用國家持續改善核能電廠營運績效
提昇容量因數， 降低跳機次數， 減少低階廢料產量

美國核能管制委員會核發電廠延役執照 (至60年),
目前已核准近 20 部機組

美國核能管制委員會允許電廠提昇功率， 總額達 4,000 MWe

2001年5月，美國布希政府發表能源政策，呼籲擴張核能

2001年， Established GEN-IV International Forum （GIF）

國家發展第四代（Gen IV）動力反應器預定於 2030 年商業運轉

4 criteria： safety, economics, sustainability, non-proliferation

2002年2月，美國布希政府確定內華達州Yucca Mountain做為高階廢料地理儲存場

2002年，芬蘭「破冰」決定興建第五部機

2002年，俄羅斯總統普亭宣示持續開發核能

2004年，石化資源價格飆漲； 2005年2月，京都議定書生效
核能發電重新獲得重視

2006年，美國Bush Administration 宣佈 GNEP (Globe Nuclear Energy Partnership)政策

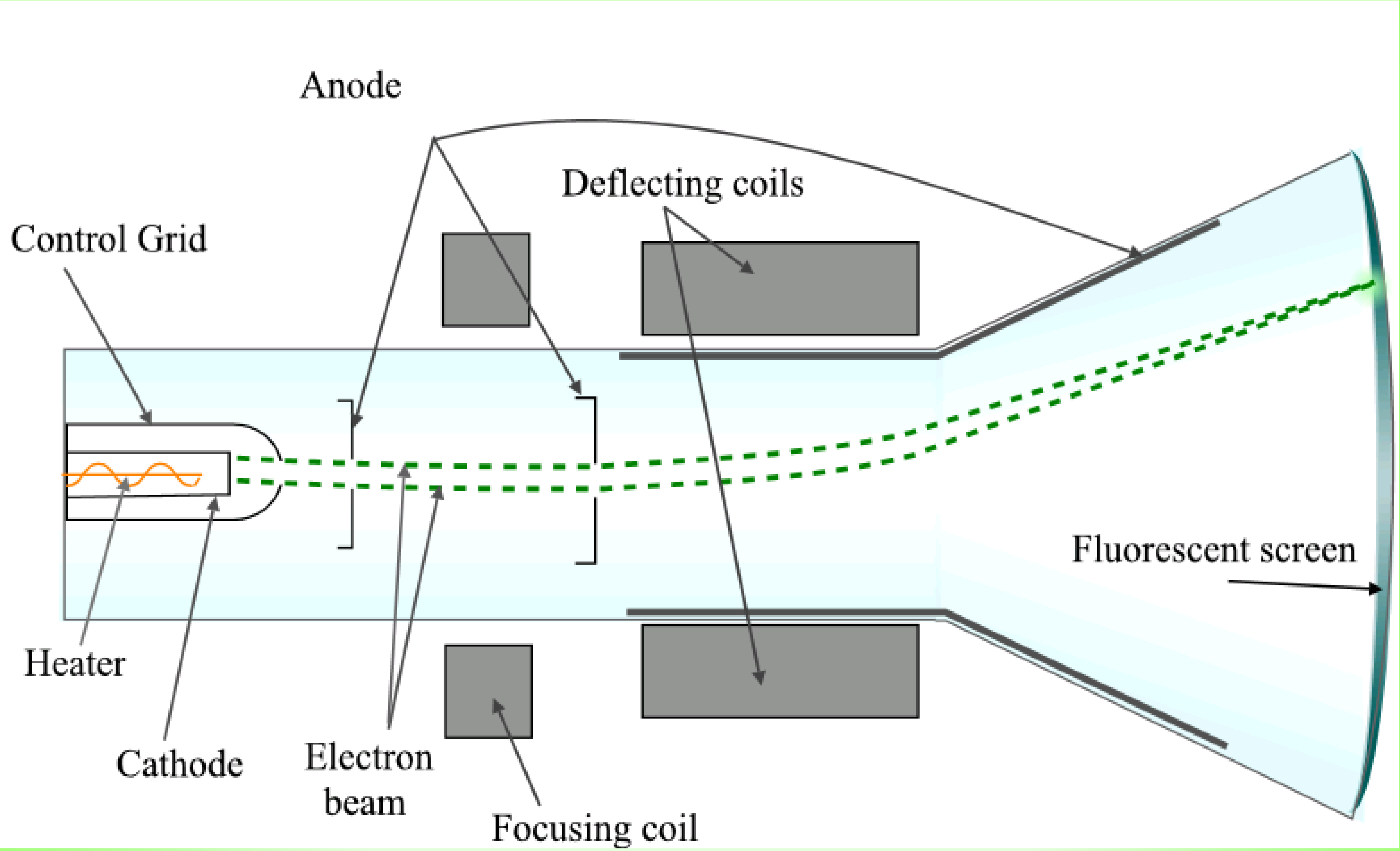
2008年，美國 歐巴馬總統宣佈暫停內華達州Yucca Mountain 做為高階廢料地理儲存場的所有活動

2011年3月11日，日本東北發生大地震，引發海嘯，導致東京電力公司的福島核能一廠發生多機組之嚴重事故，大量放射性物質釋放到外界環境

國內核能發電現況

核子動力反應器類別

	燃料	冷卻劑	緩和劑
快中子反應器(孳生反應器)			
LMFBR	高度濃縮鈾或鈽	液態金屬	-------
熱(慢)中子反應器			
輕水式反應器 (Light Water Reactor)			
壓水式(PWR)	低度濃縮鈾	普通水	普通水
沸水式(BWR)	低度濃縮鈾	普通水	普通水
重水式反應器(Heavy Water Reactor)			
CANDU	天然鈾	普通水	重水
石墨水冷反應器			
RBMK	低度濃縮鈾	普通水	石墨
氣冷式反應器			
GCR	低度濃縮鈾	CO2	石墨
HTGR	低度濃縮鈾	氦氣	石墨

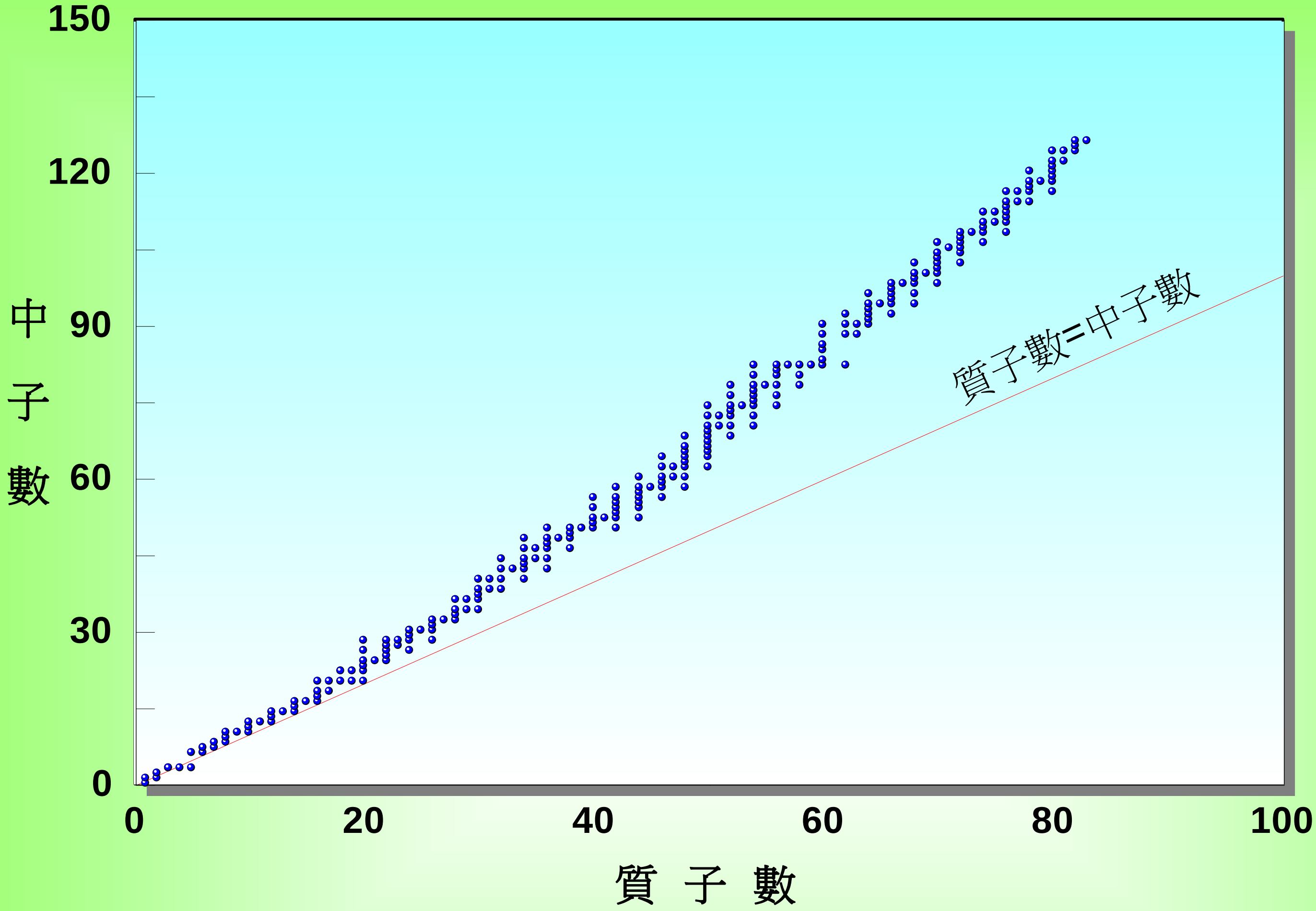


invented by German physicist Karl Ferdinand Braun in 1879

陰極射線管的發明

German physicist
Karl Ferdinand Braun

Shared the Nobel Prize for physics with Marconi for "contributions to the development of wireless telegraphy."



自然界穩定存在之核種，其原子核內質子與中子數的配比關係。
較輕的核種中其質子數約略等於中子數而較重核種的中，
中子數大於質子數

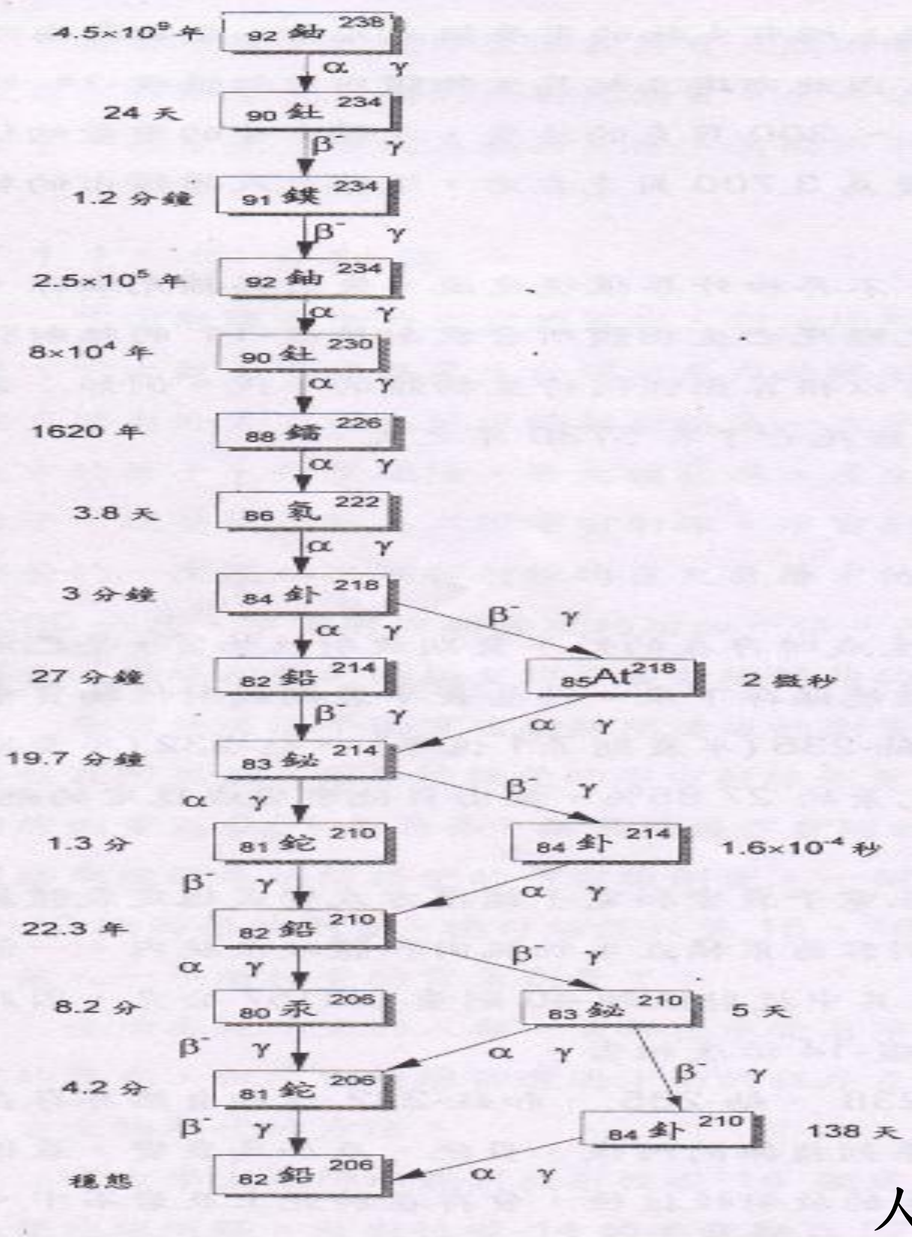


圖 7.1 ：鈾-238 衰變系列。

$$U_{92}^{238} \Rightarrow Th_{90}^{234} + He_2^4(\alpha),\ T_{1/2} = 4.5\times10^9 \text{ year}$$

$$Th_{90}^{234} \Rightarrow Po_{91}^{234} + \beta_{-1}^{0},\ T_{1/2} = 24\,days$$

$$\vdots$$

$$Rn_{86}^{222} \Rightarrow Po_{84}^{218} + He_2^4(\alpha),\ T_{1/2} = 3.8 \text{ day}$$

$$\vdots$$

$$Pb_{82}^{206}$$

鈾-238 (半衰期45億年)

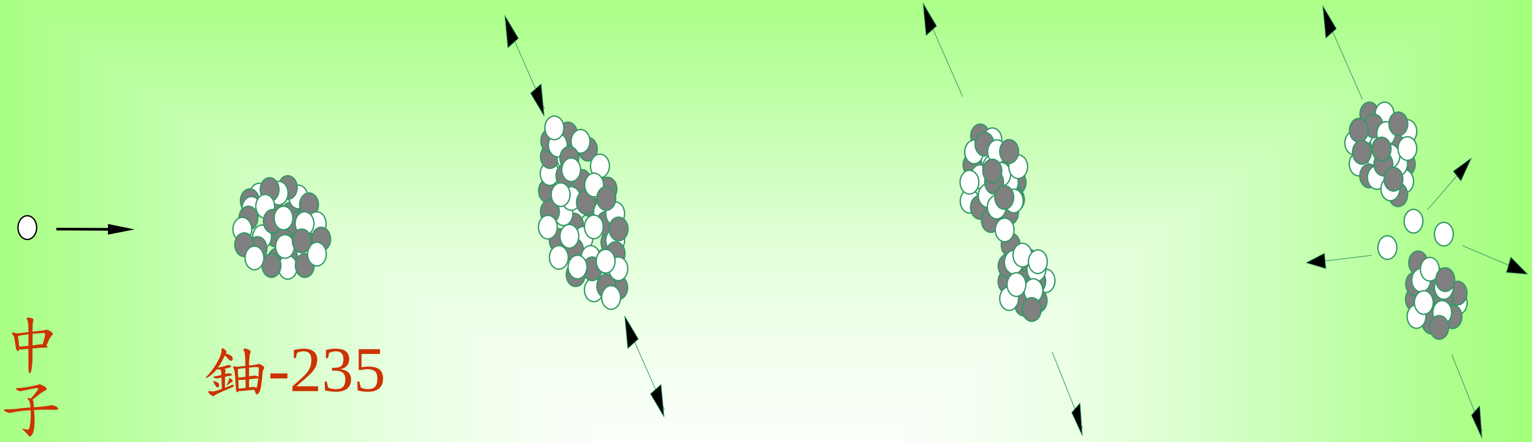
鈾-235 (半衰期7.1億年)

釷-232 (半衰期140億年)

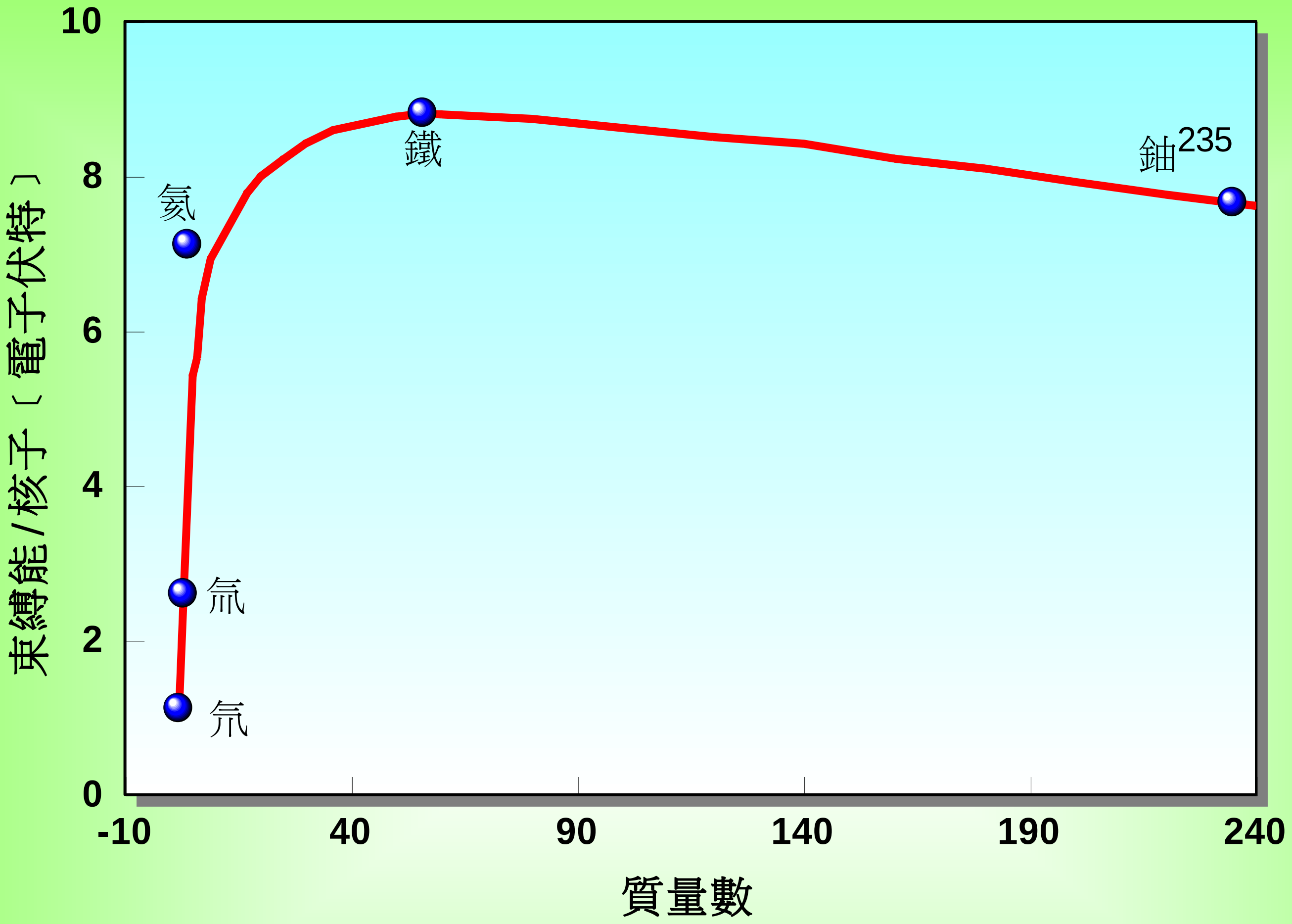
鉫-87 (半衰期480億年)

鉀-40 (半衰期13億年)

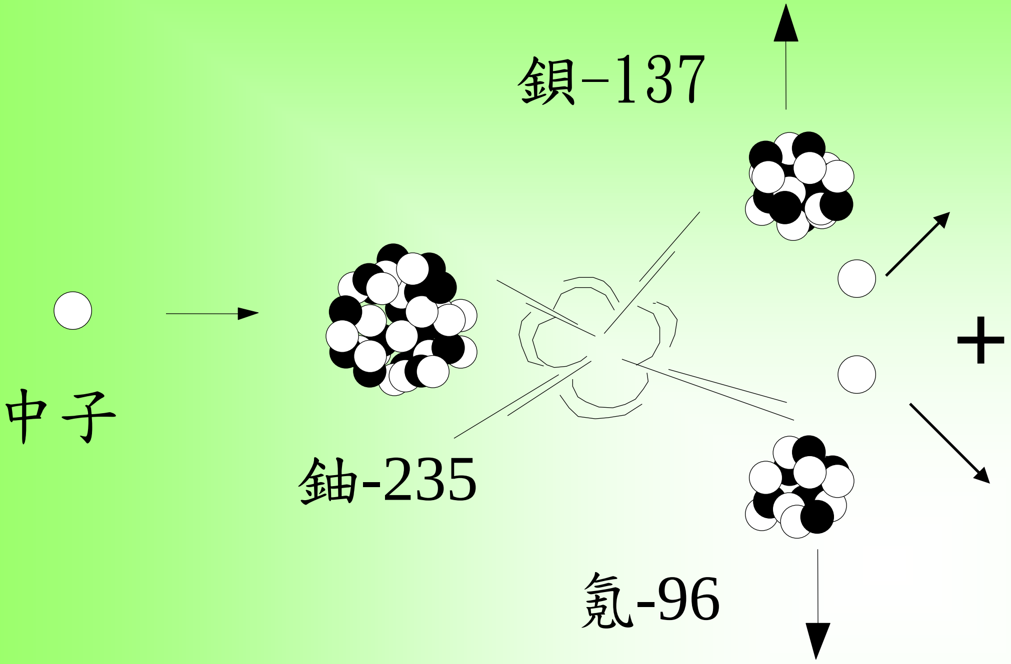
人體的鉀-40活度估算約為4000貝克



中子誘發鈾-235核分裂的過程。從左邊到右邊：一個中子撞擊鈾-235核，形成鈾-236核。激發狀態鈾-236作劇烈啞鈴狀之震盪。此時核內正電荷互相排斥，導致啞鈴狀結構瓦解，產生兩個質量數較小的原子核，並釋放出數個中子。



核子平均束縛能與原子核質量數間的關係。輕原子核束縛能隨質量數的增加而迅速增加；鐵-56的平均束縛能達到極大值，之後核子平均束縛能隨著原子核質量數的增加緩緩下降。



鋇-137

中子

鈾-235

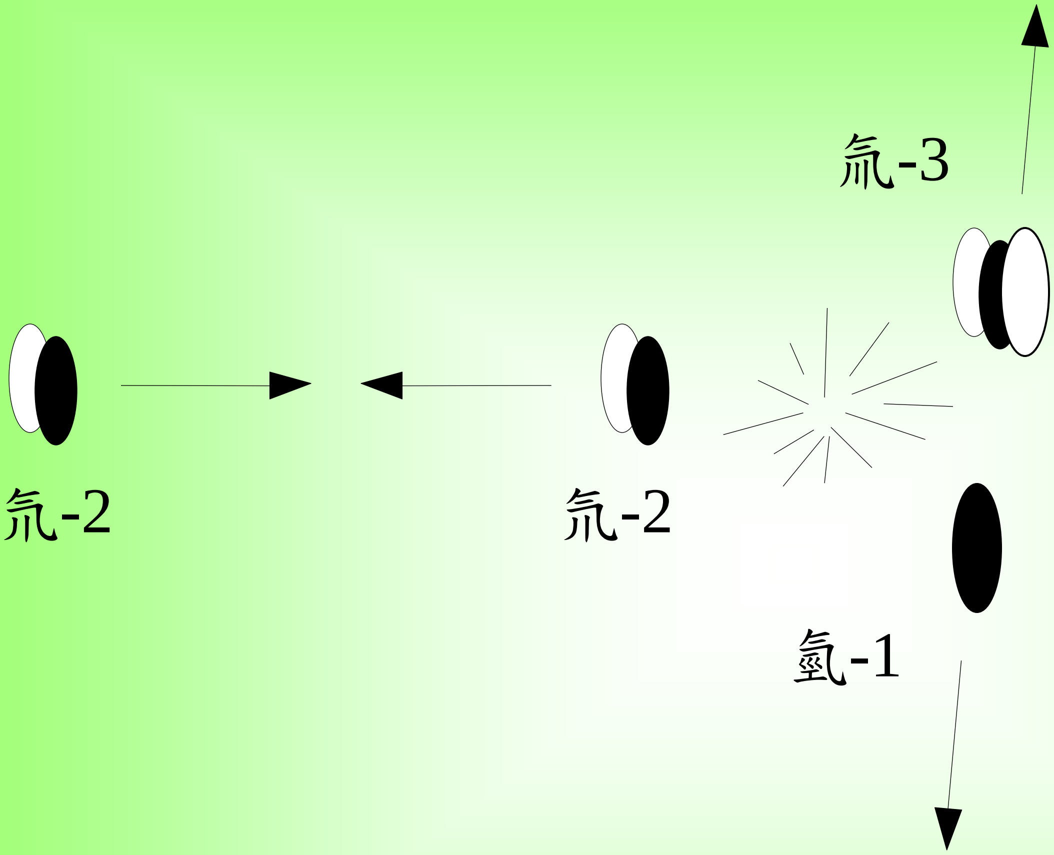
氪-96

＋ ✸ 193.6百萬電子伏特能量

$$\Delta E = \Delta m C^2$$

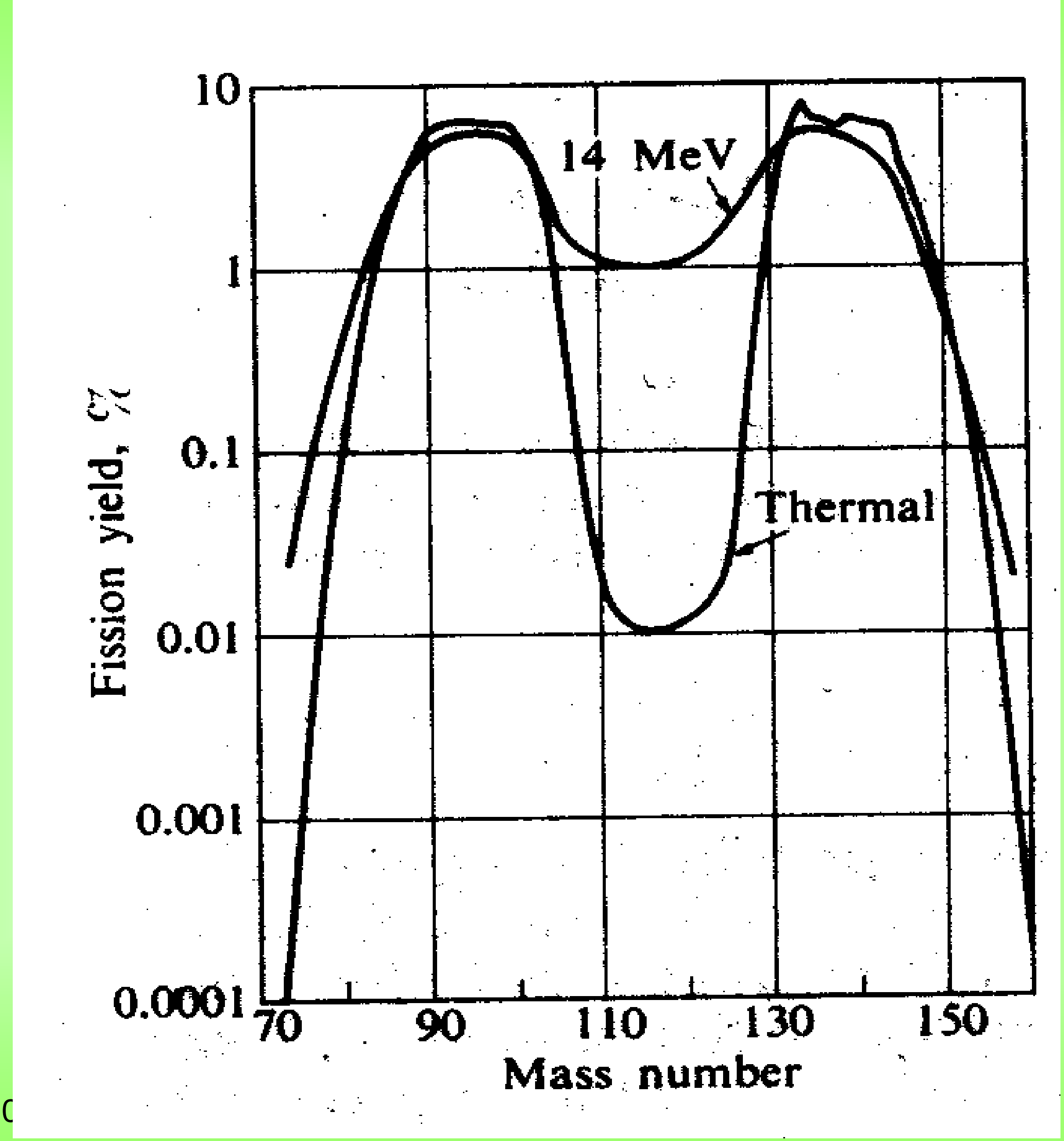
1克鈾的分裂可產生 960 千瓦-天的能量
1公斤鈾的分裂相當於16000噸的黃色炸藥

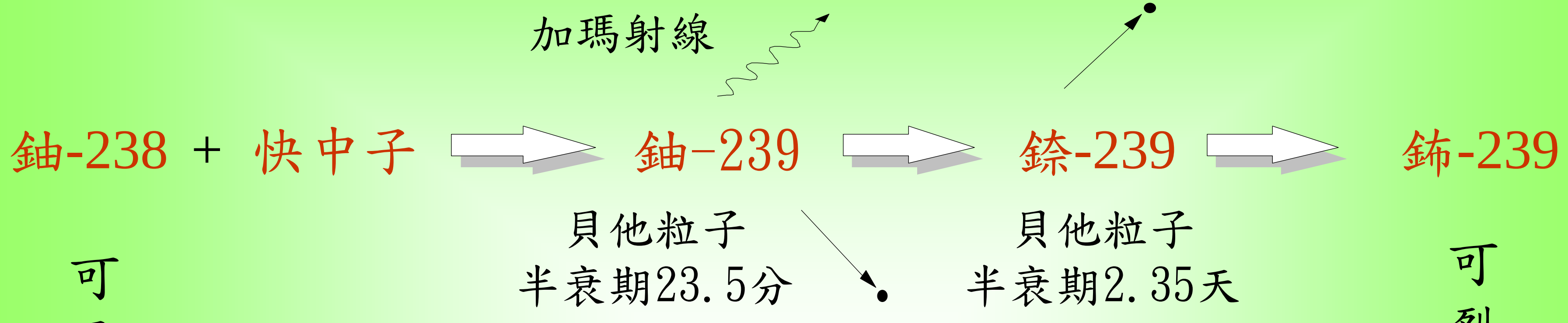
核分裂連鎖反應



+✹ 4.02百萬電子伏特能量

核融合


10
1
0.1
0.01
0.001
0.0001
Fission yield, %
14 MeV
Thermal
70
90
110
130
150
Mass number



加瑪射線

鈾-238 + 快中子 → 鈾-239 → 錼-239 → 鈽-239

貝他粒子
半衰期23.5分

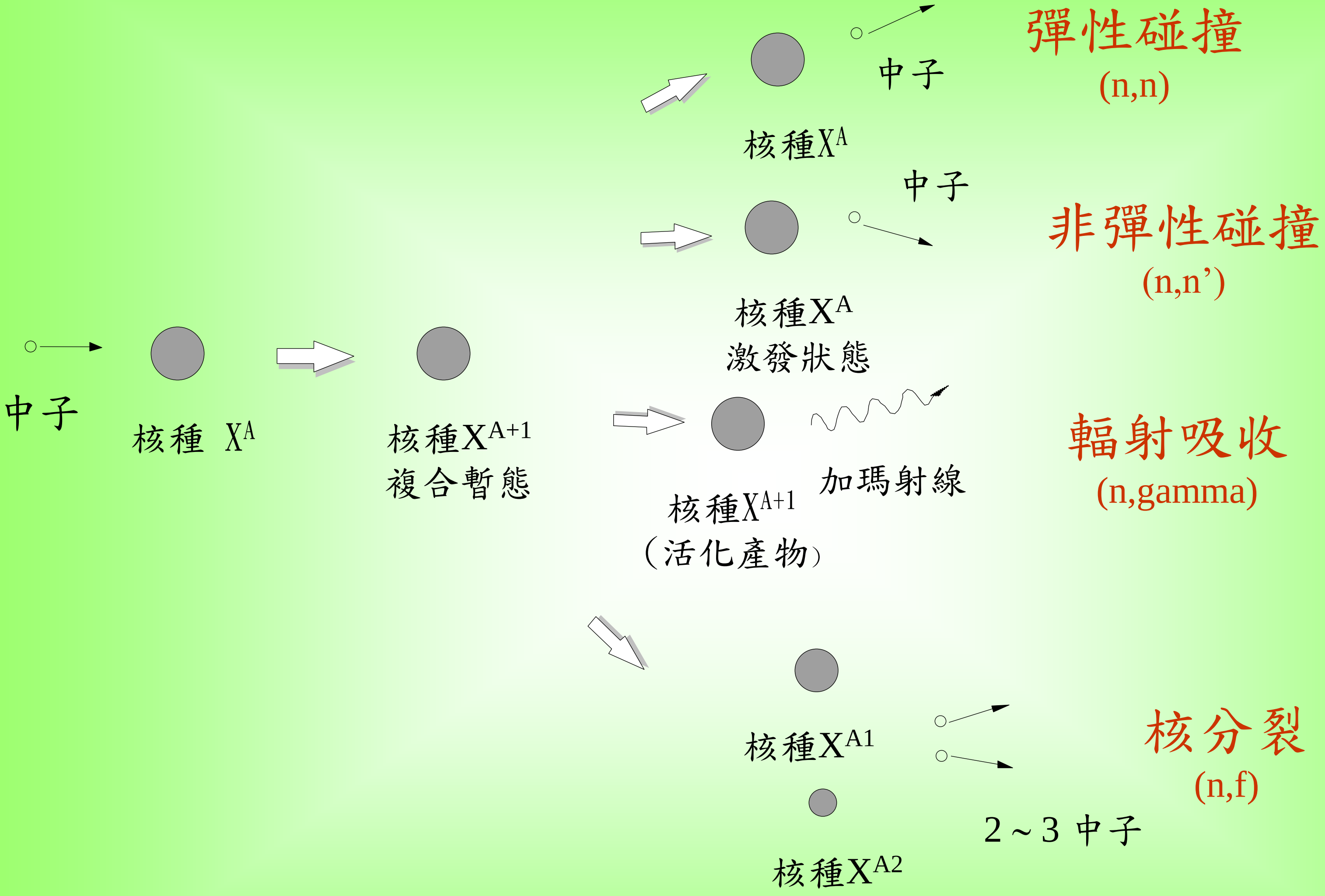
貝他粒子
半衰期2.35天

可孕物質

可裂物質

鈾 (Uranium); Uranus (天王星)
錼 (Neptunium); Neptune (海王星)
鈽 (Plutonium): Pluto (旻王星)

可裂物質鈽-239製造程序



中子

核種 X^{A}

核種X^{A+1}
複合暫態

核種X^{A}

中子

彈性碰撞
(n,n)

中子

核種X^{A}
激發狀態

非彈性碰撞
(n,n’)

核種X^{A+1}
（活化產物）

加瑪射線

輻射吸收
(n,gamma)

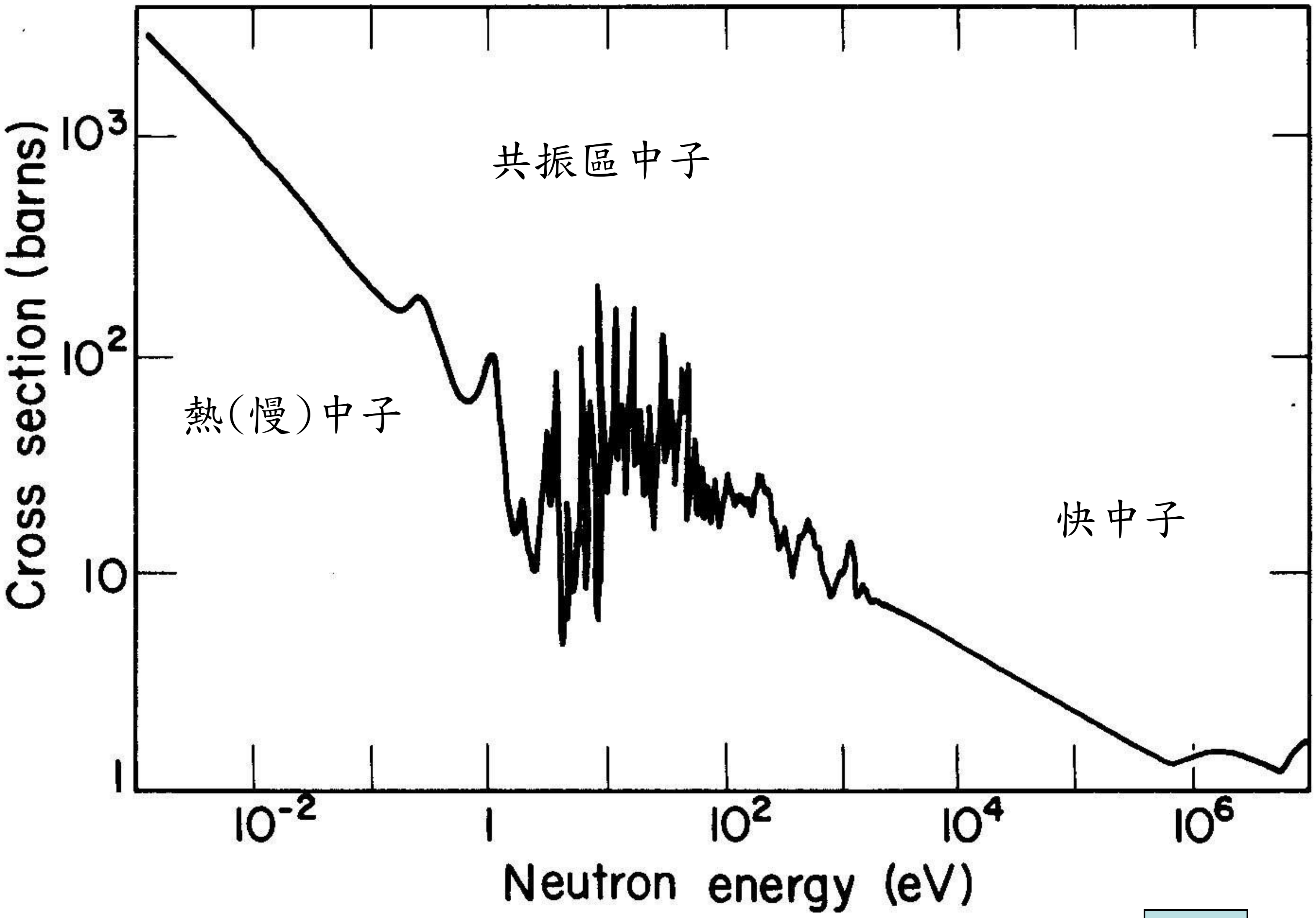
核種X^{A1}

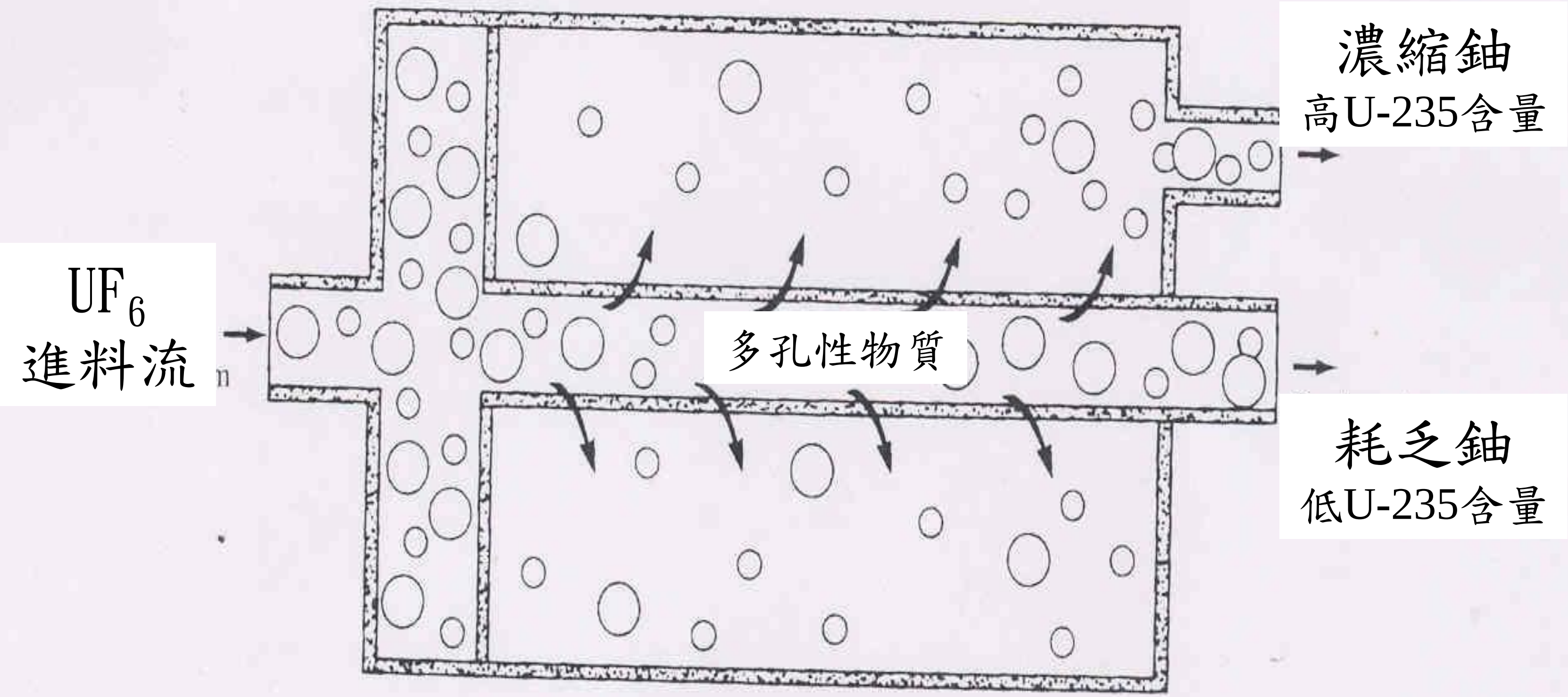
核種X^{A2}

2～3 中子

核分裂
(n,f)

中子與原子核作用分類示意圖


共振區中子
熱(慢)中子
快中子
Cross section (barns)
10^3
10^2
10
1
10^{-2}
1
10^2
10^4
10^6
Neutron energy (eV)



UF_6
進料流

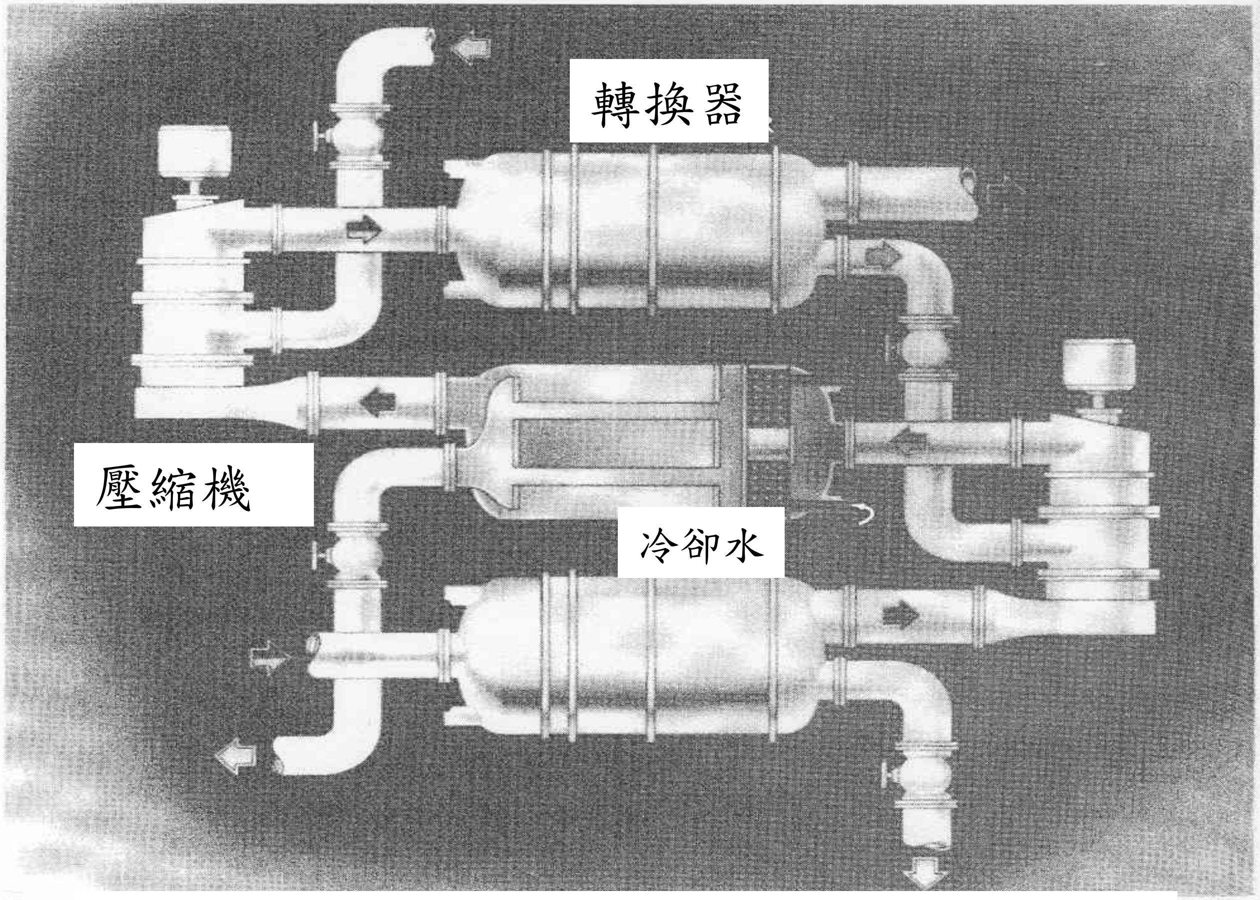
濃縮鈾
高U-235含量

多孔性物質

耗乏鈾
低U-235含量

氣體擴散之擴散器

濃縮鈾 (enriched uranium), 耗乏鈾 (depleted uranium)


轉換器
壓縮機
冷卻水

濃縮鈾工廠

耗費大量電能, 美國之鈾濃縮廠為全國之最大電能用戶

鈾有兩種同位素– U-235(0.7%) 及 U-238 (99.3%);
僅 U-235 可維持核分裂連鎖反應

中子反應截面與中子能量(中子速度)有關
慢中子誘發 U-235 核分裂反應的反應截面
較快中子的反應截面三個數量級
– 即慢中子較易誘發 U-235 之核分裂反應

核分裂反應所釋出之中子為快中子
– 若燃料中之 U-235 含量不夠高,
須將中子速度減慢以增加中子誘發核分裂反應的機率

中子減速的方法: 與其他低質量數的原子核碰撞
緩和劑(減速劑), moderator

H-核 (H_2O, 水), 但 H-核 會強烈吸收中子
使用水為緩和劑之反應器, 無法僅靠天然鈾即達到臨界

D-核 (D2O, 重水), C-核 (石墨);

緩和劑的質量數越低, 減速的效果越好

緩和劑的質量數越大時, 快中子在減速過程被重核 (U-238) 吸收的機會也越高

設計鈽元素生產用反應器時, 應採用質量數較高的核種 (重水或石墨)為緩和劑

使用普通水為緩和劑之反應器, 其鈽元素之產生量偏低, 較不易造成核武器的擴散

輕水式(普通水)式反應器的燃料會停留在反應器內達三年之久, 部分Pu-239會在吸收中子成為 Pu-240,Pu-240 會自發性的分裂釋出中子,造成核彈設計上的困擾

鈽生產反應器須具有鈽停機即可換燃料的特性

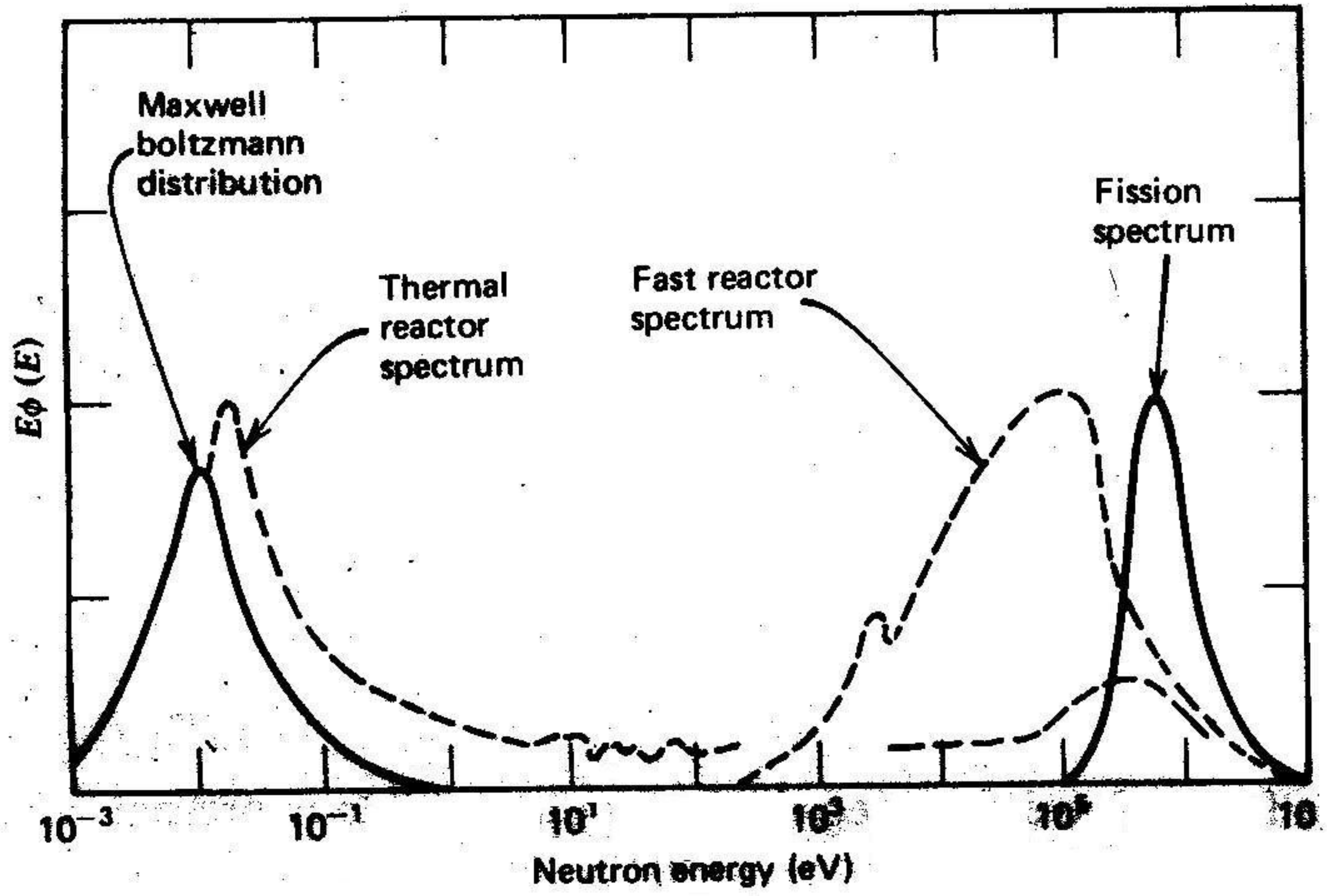
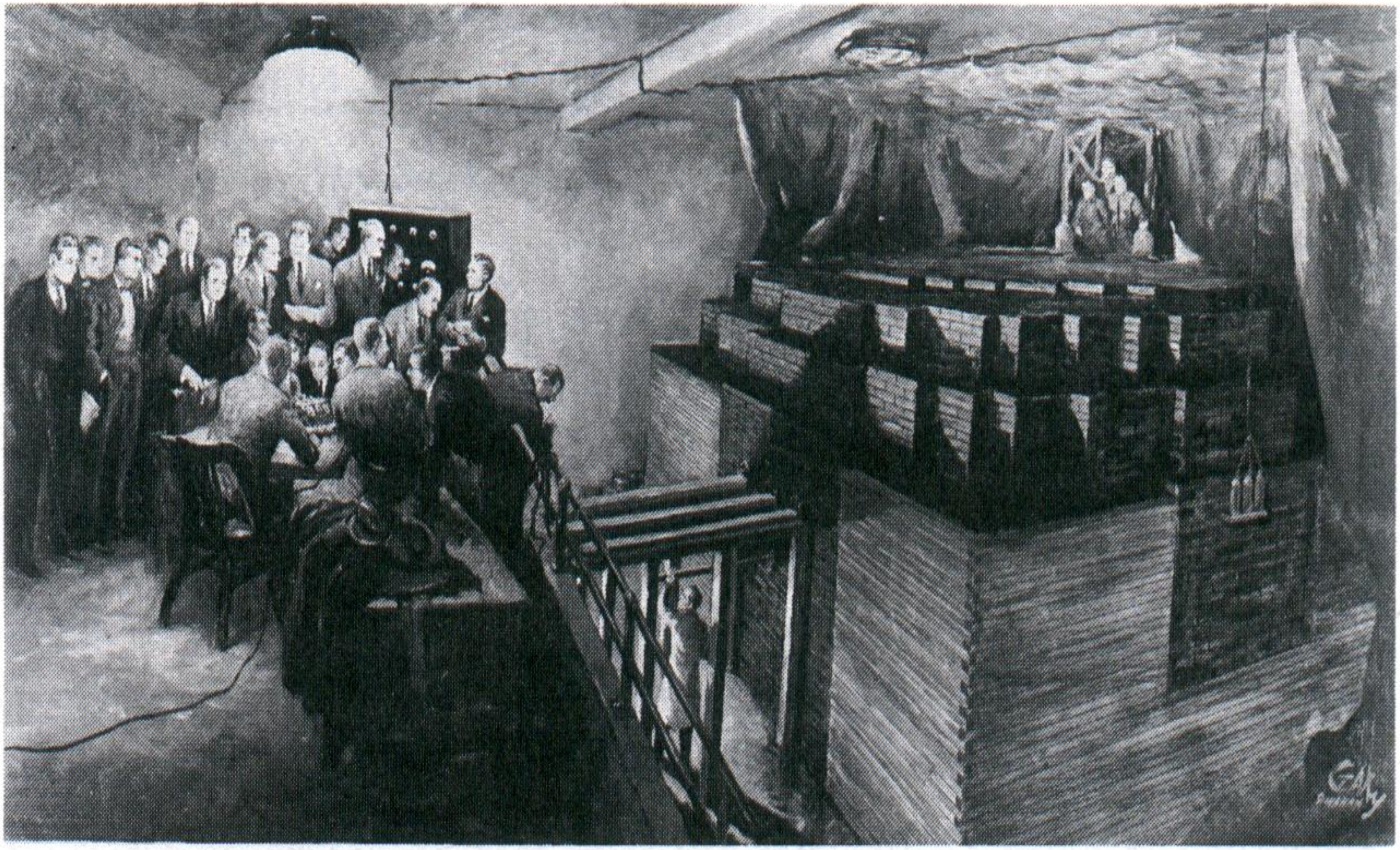


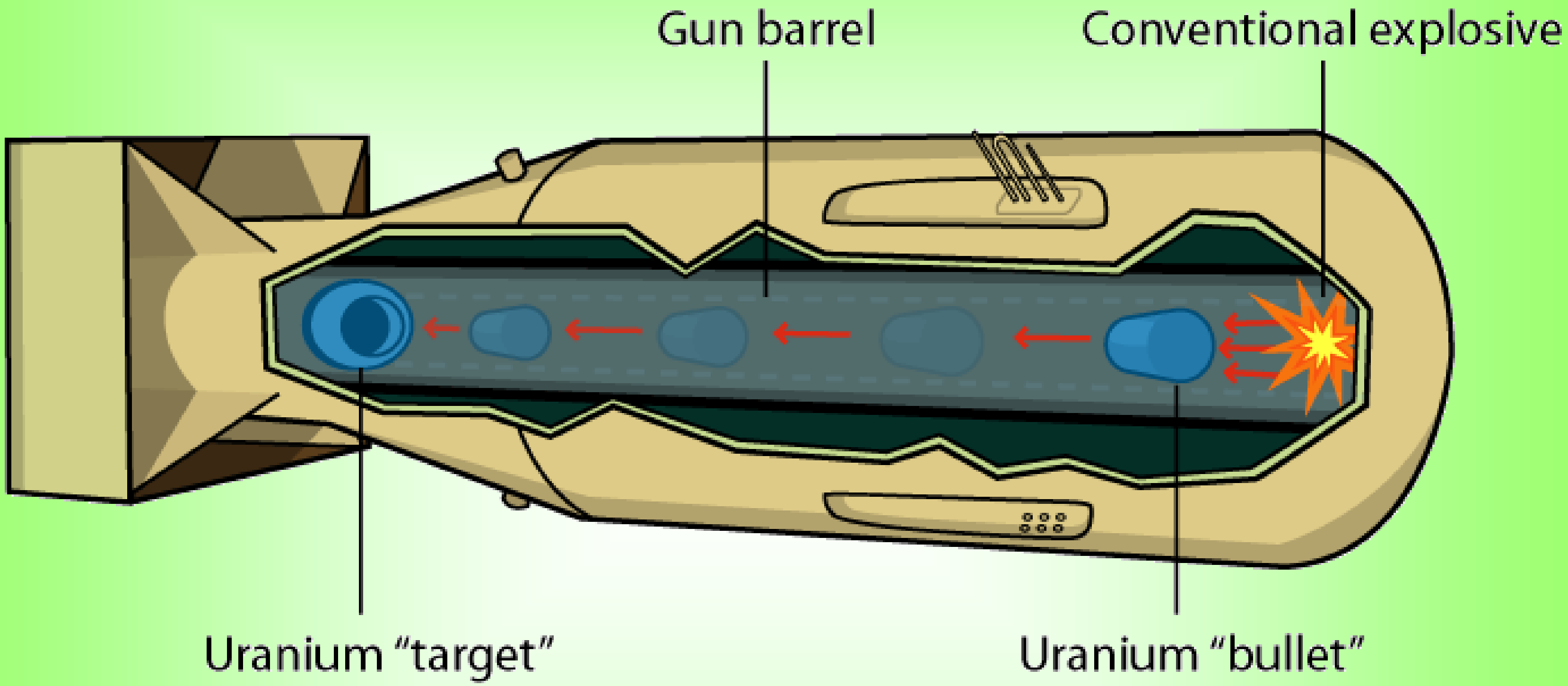
FIGURE 1-5 Typical neutron flux spectra.

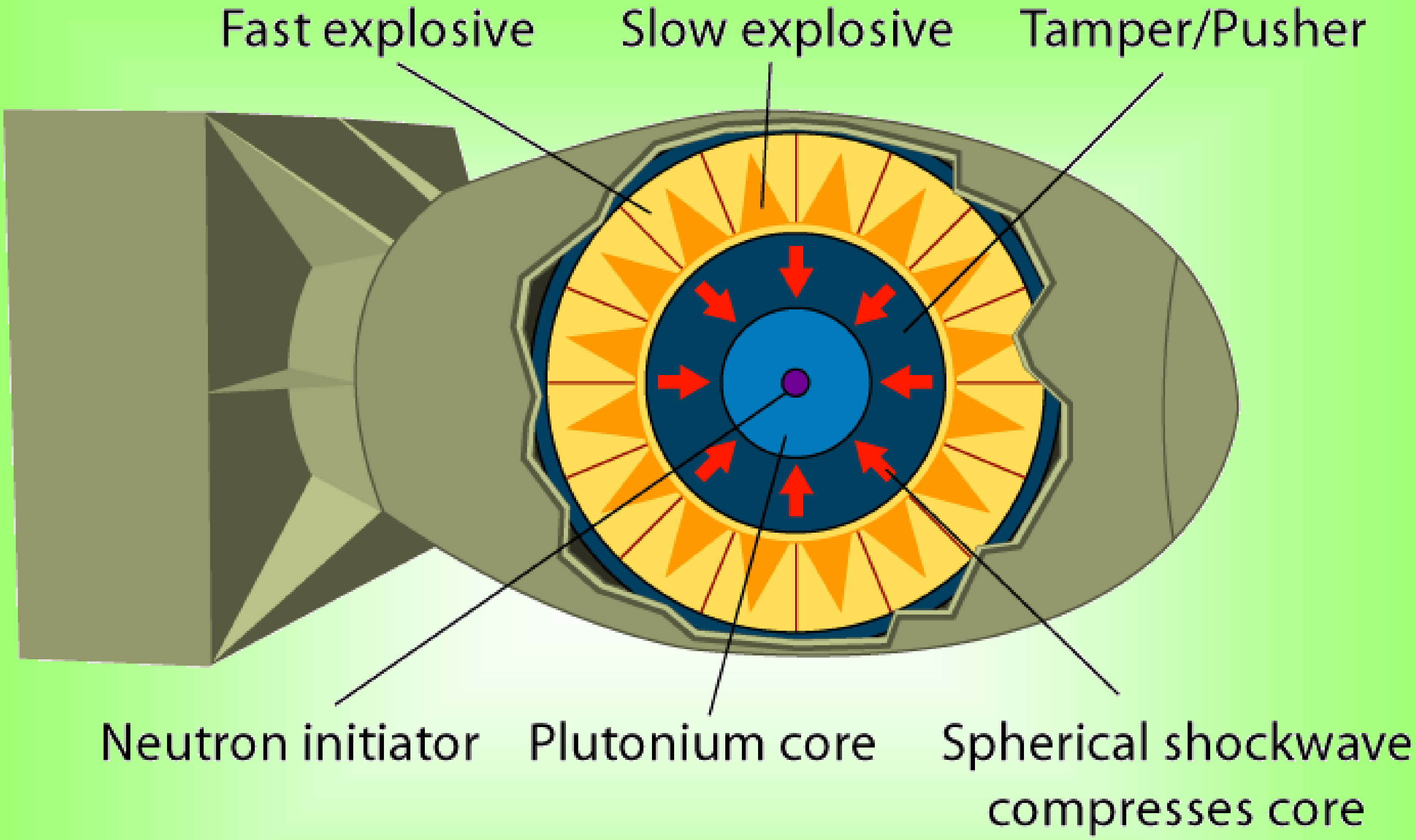
反應截面(Cross Section)

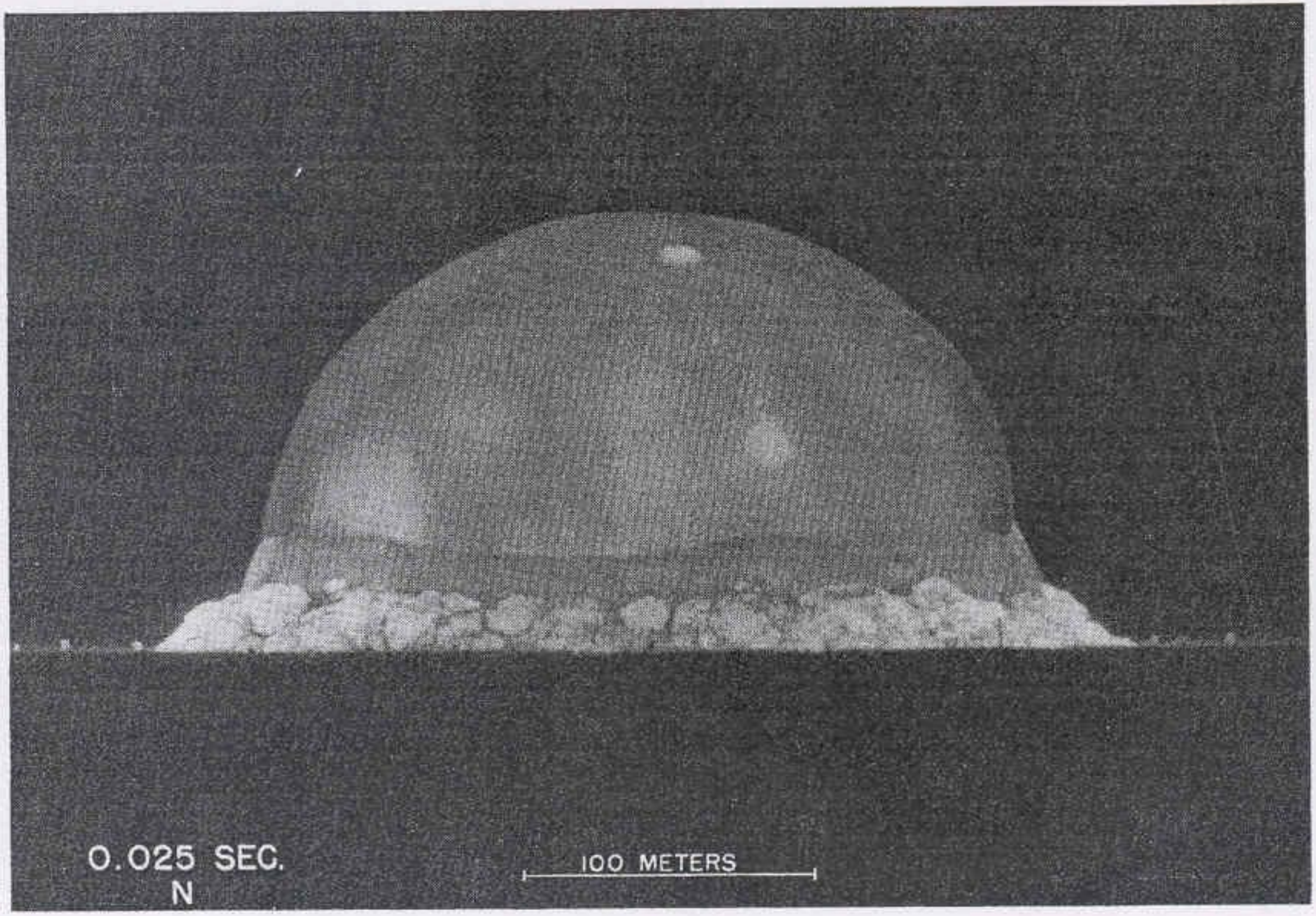


Chicago Pile - 1

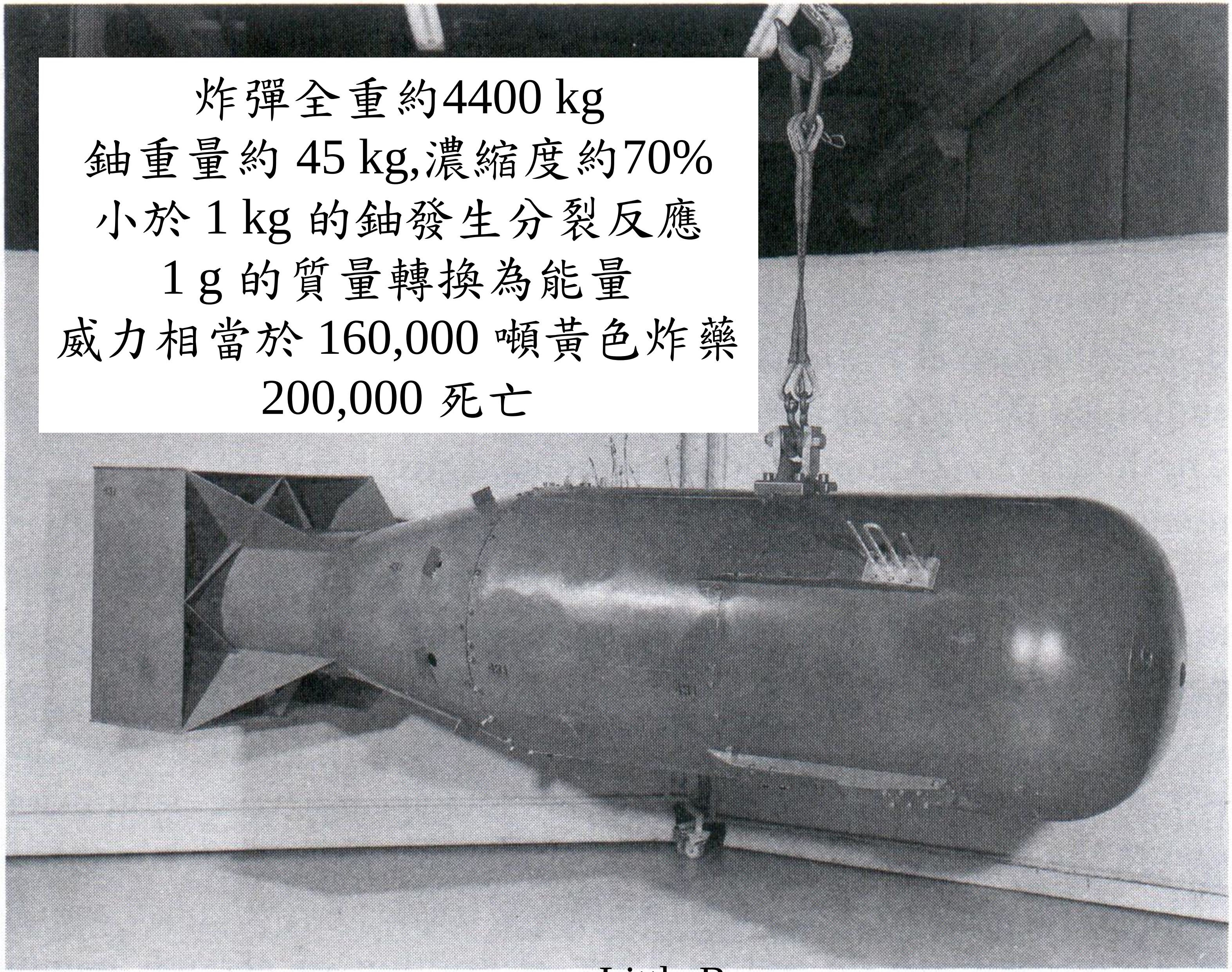
Hanford Site in 1945. B-Reactor is the building just to the right of the water tower.


Gun barrel
Conventional explosive
Uranium “target”
Uranium “bullet”


Fast explosive
Slow explosive
Tamper/Pusher
Neutron initiator
Plutonium core
Spherical shockwave compresses core

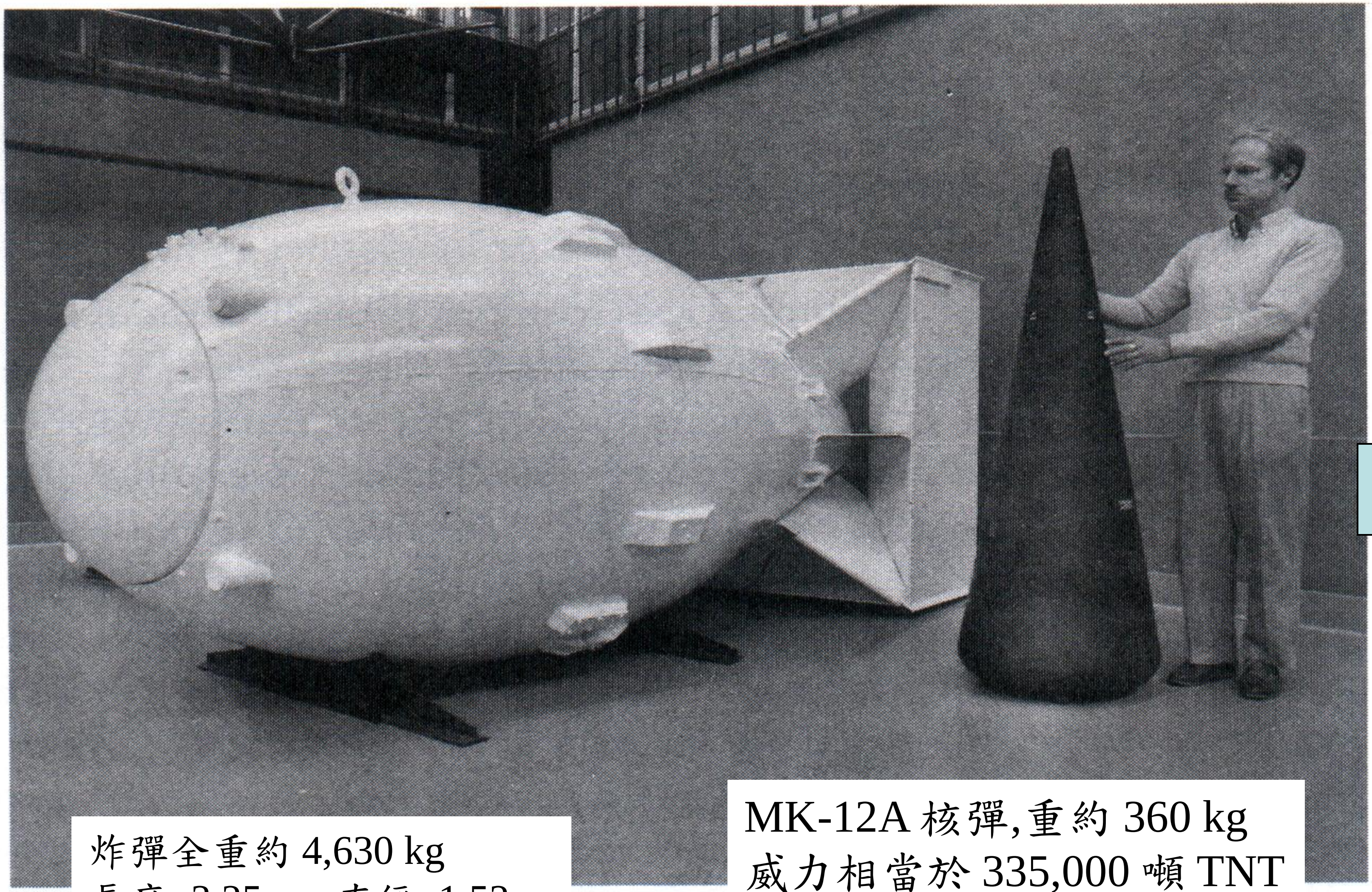


The fireball of the Trinity test, shown just 0.025 second after detonation. (Los Alamos National Laboratory)



炸彈全重約4400 kg
鈾重量約 45 kg,濃縮度約70%
小於 1 kg 的鈾發生分裂反應
1 g 的質量轉換為能量
威力相當於 160,000 噸黃色炸藥
200,000 死亡

Little Boy

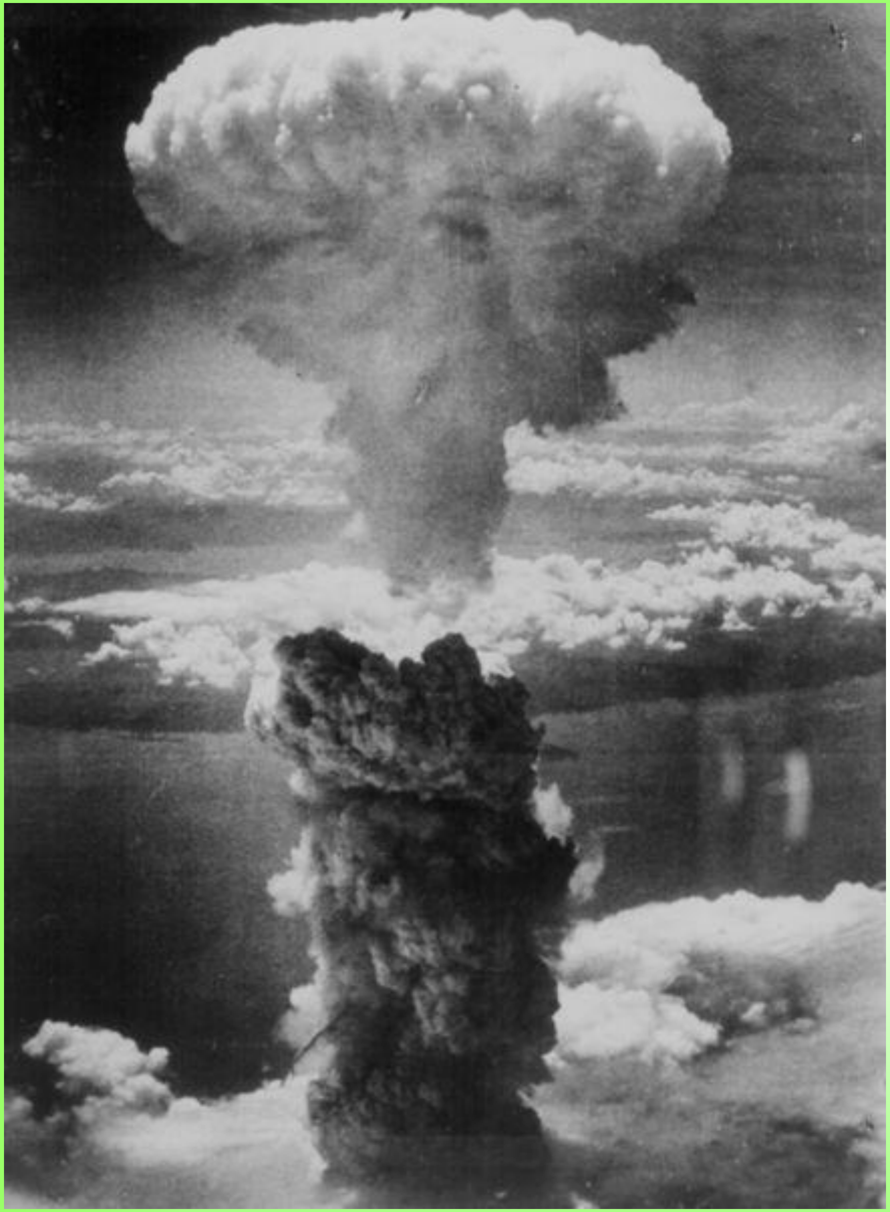


炸彈全重約 4,630 kg
長度: 3.25 m, 直徑: 1.52 m
威力相當於 22,000 噸 TNT
110,000 人死亡

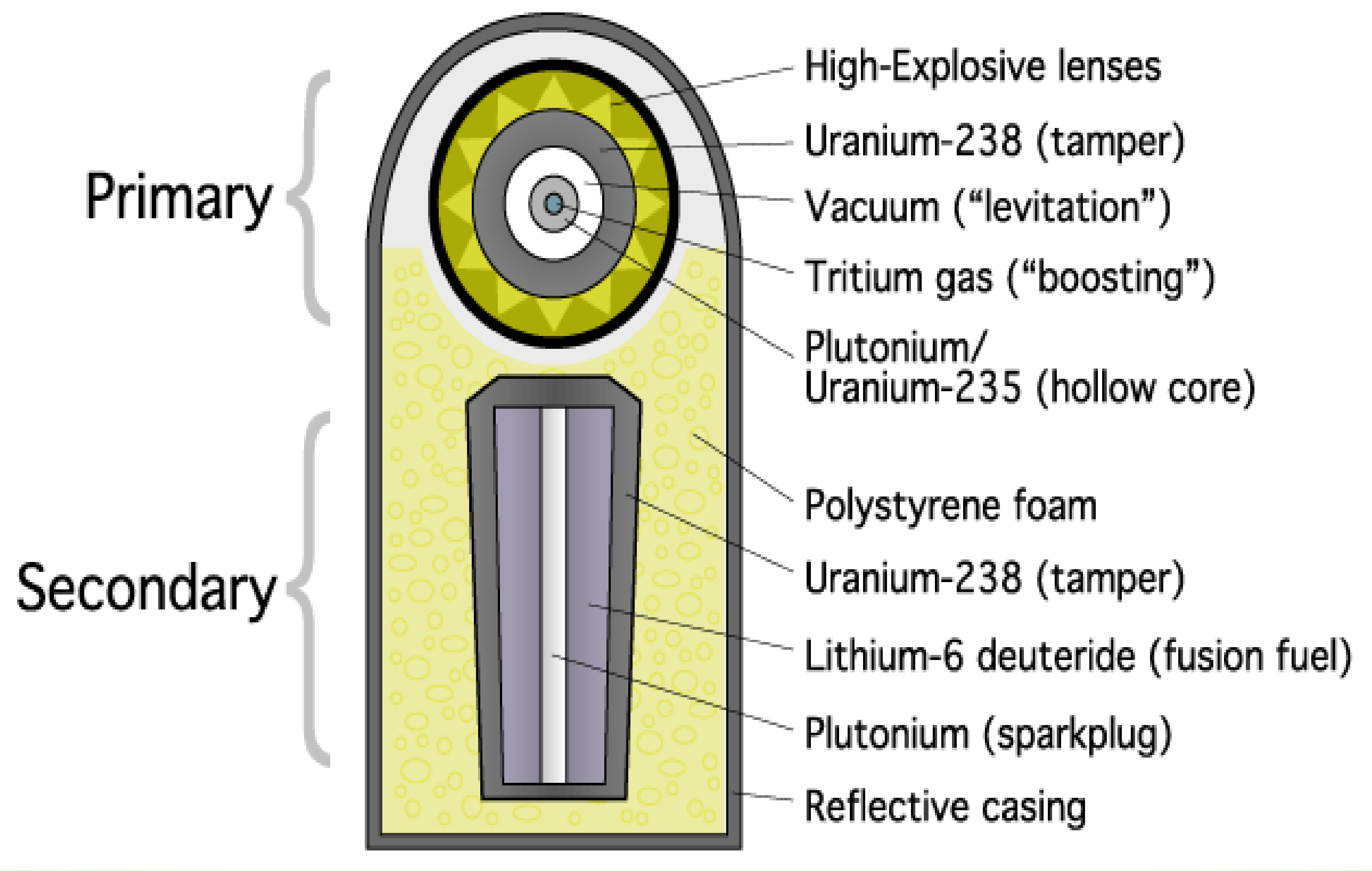
MK-12A 核彈,重約 360 kg
威力相當於 335,000 噸 TNT
一枚義勇兵三號飛彈可攜帶
三個 MK-12A 核彈

Fat Man

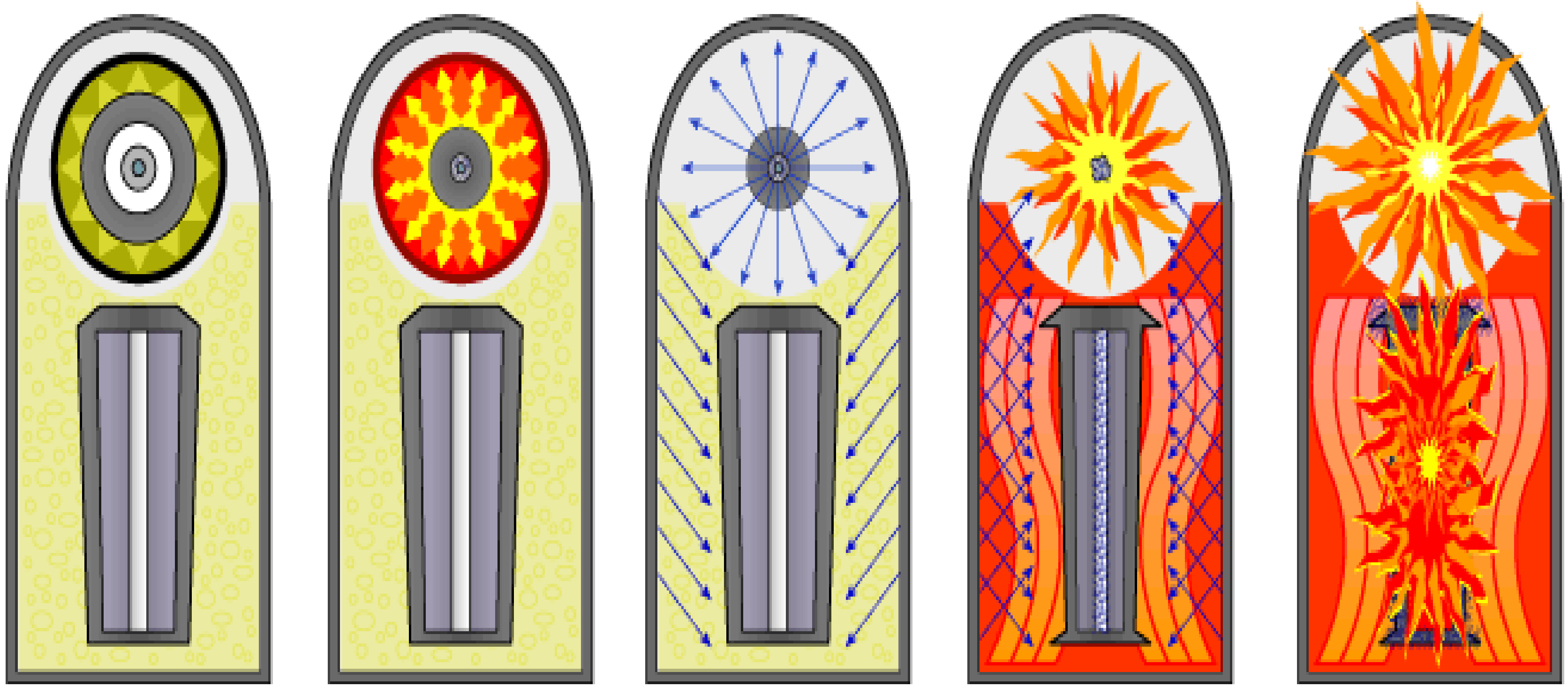
The Atomic Bomb Dome in Hiroshima, which has been preserved as a memorial of the blast.



The mushroom cloud of the atomic bombing of Nagasaki, Japan, 1945, rose some 18 kilometers (11 mi) above the hypocenter



One possible version of the Teller–Ulam configuration of Hydrogen Bomb



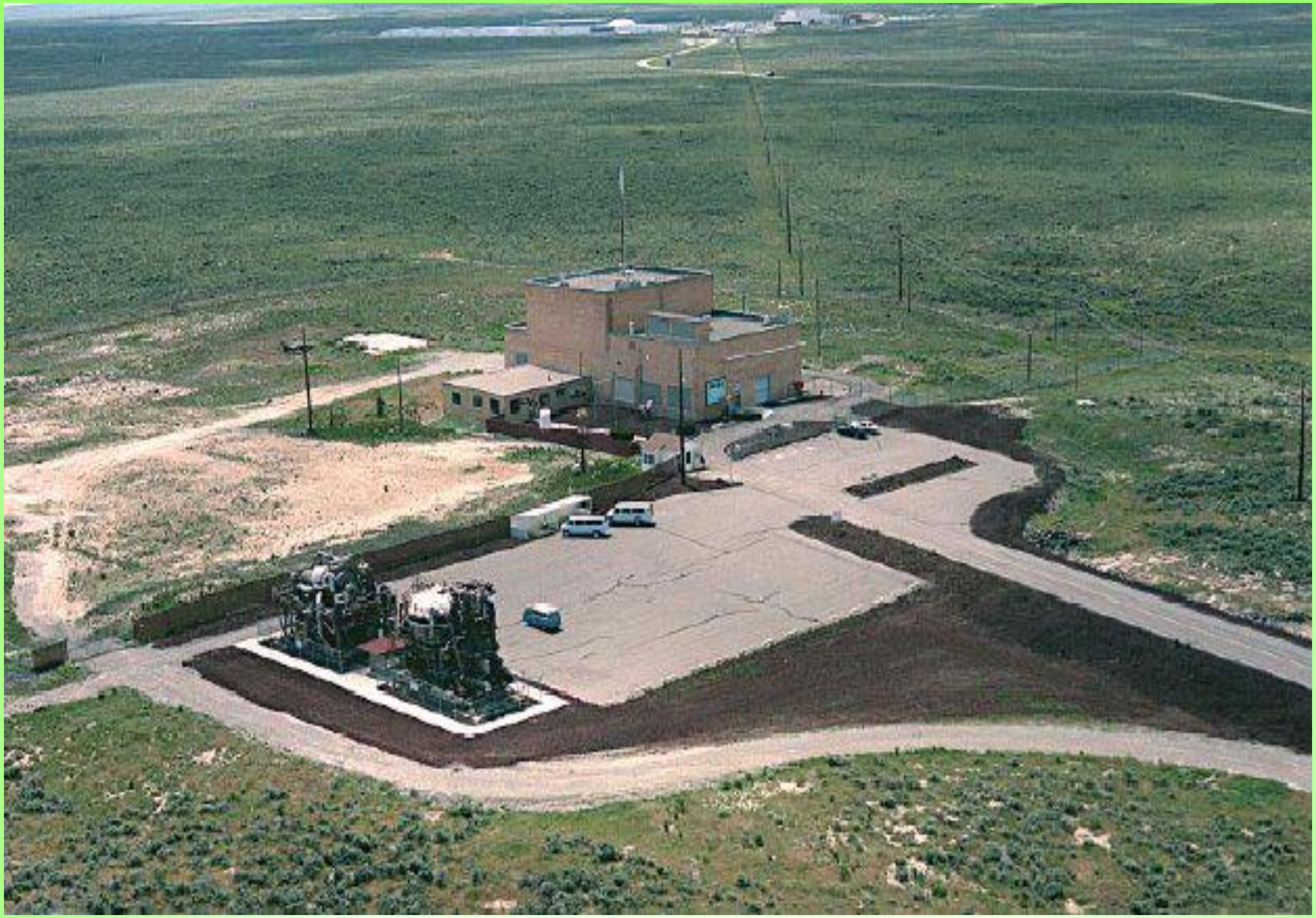
1. Warhead before firing; primary (fission bomb) at top, secondary (fusion fuel) at bottom, all suspended in polystyrene foam.

2. HE fires in primary, compressing plutonium core into supercriticality and beginning a fission reaction.

3. Fissioning primary emits X-rays which reflect along the inside of the casing, irradiating the polystyrene foam.

4. Polystyrene foam becomes plasma, compressing secondary, and plutonium sparkplug begins to fission.

5. Compressed and heated, lithium-6 deuteride fuel begins fusion reaction, neutron flux causes tamper to fission. A fireball is starting to form...

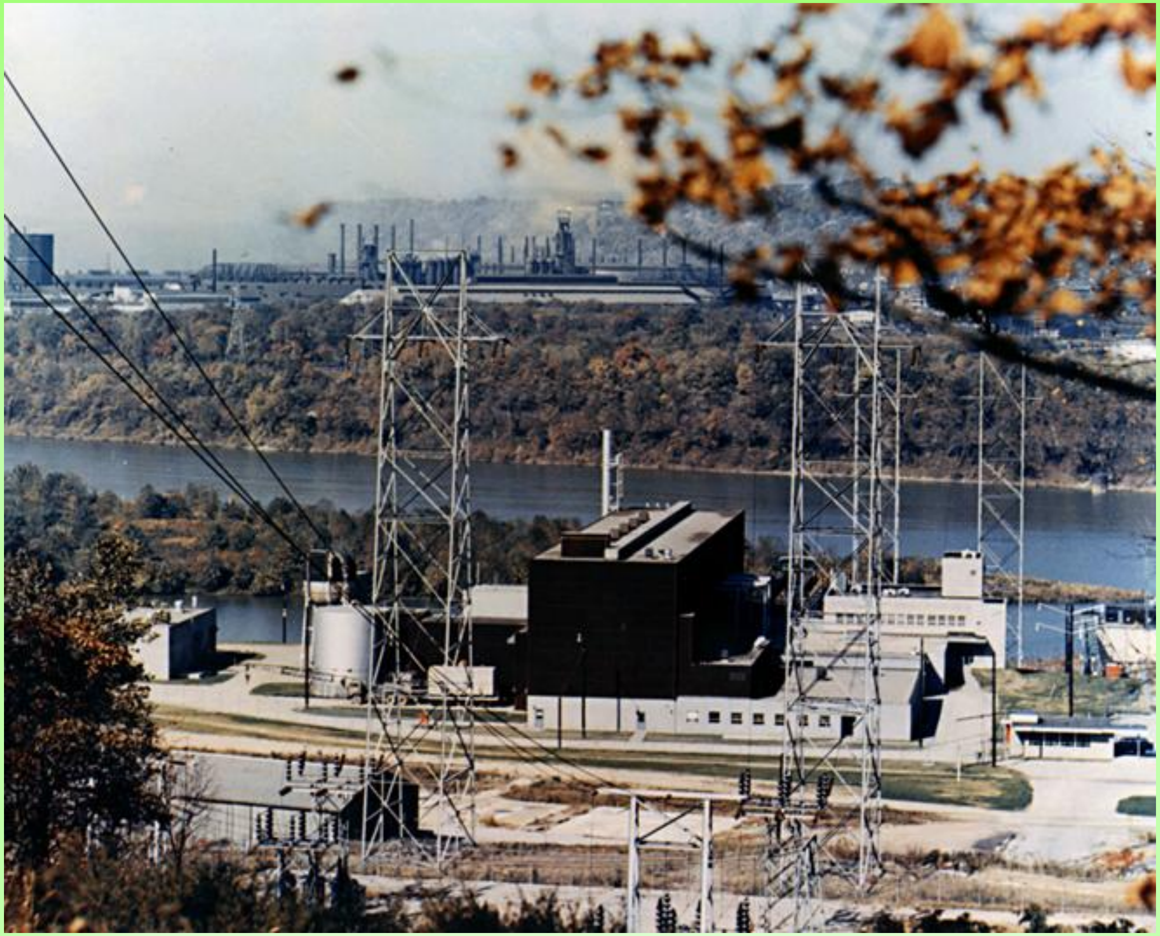


Experimental Breeder Reactor Number 1 in Idaho, the first power reactor. The reactor is in the building top right, the two structures lower left are reactors from the Aircraft Nuclear Propulsion Project

國際原子能總署（International Atomic Energy Agency（IAEA））

Seawolf Attack Submarine of US Navy

Calder Hall unit 1.



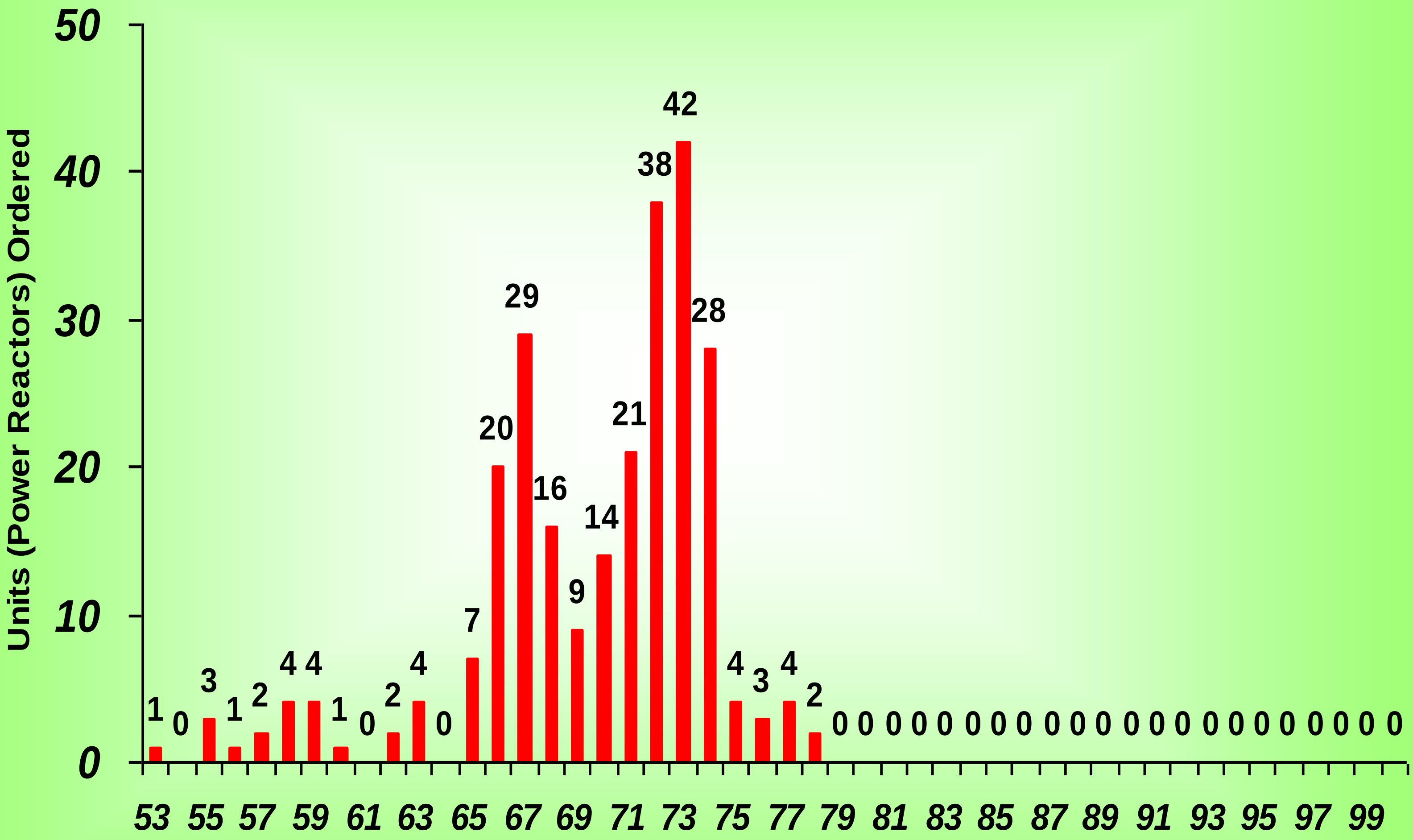
Shippingport reactor was the first full-scale nuclear power plant in the United States

Beaver County, Pennsylvania

第一次石油危機

- 1960中東和非洲發現大量油田
- 1960-1970，石油價格每桶約2美元
- 1969年，格達費掌權，下令減產石油
- 1973，第四次中東戰爭爆發
- 1973-1974年初，油價從每桶3元飆到12元
- 1973年，美國電力公司訂購 42 部核能機組
- 至1974，美國電力公司累計訂購 210 部機組
- 核燃料產能大幅擴充

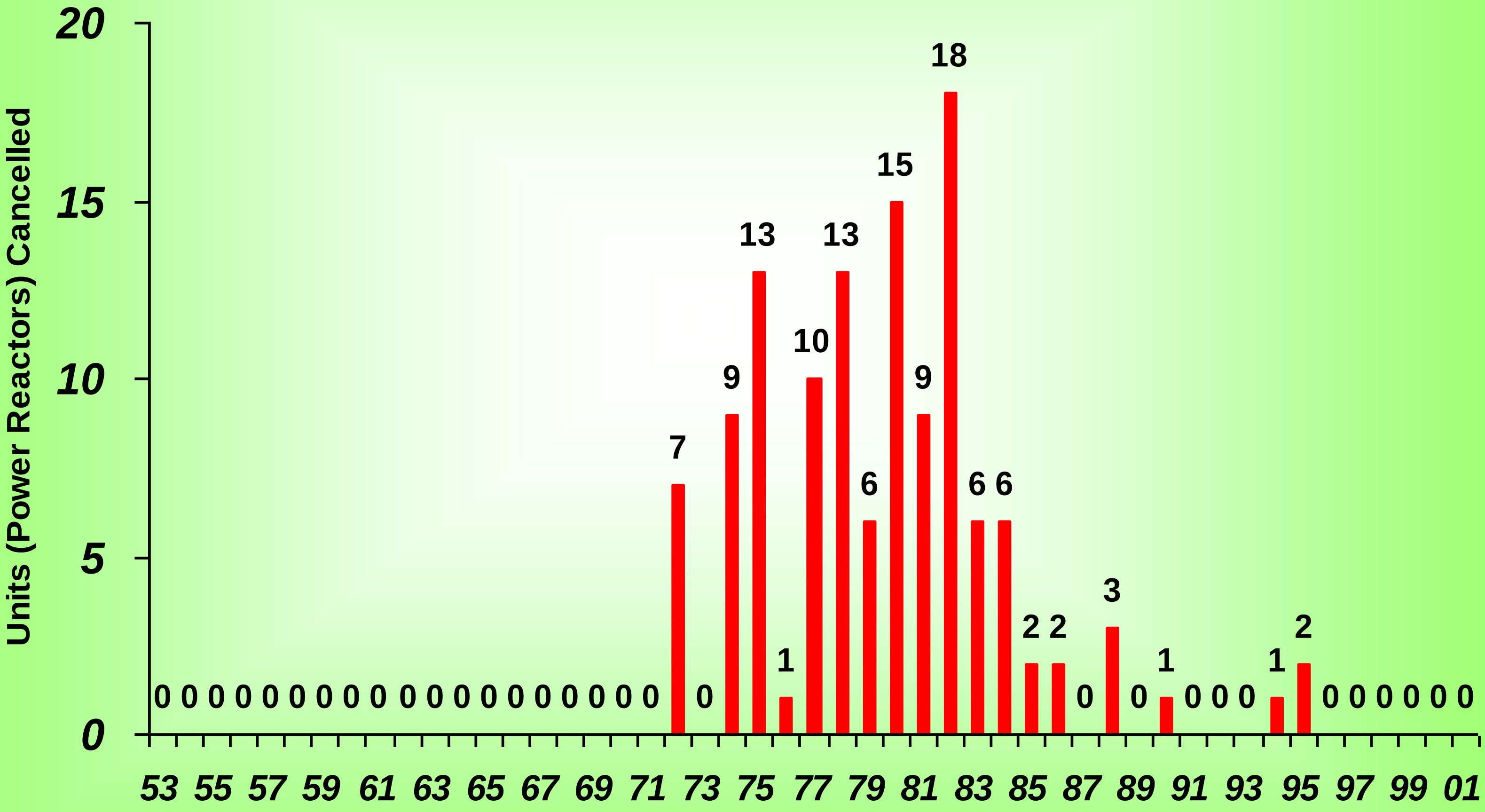
美國核能電廠訂購狀況



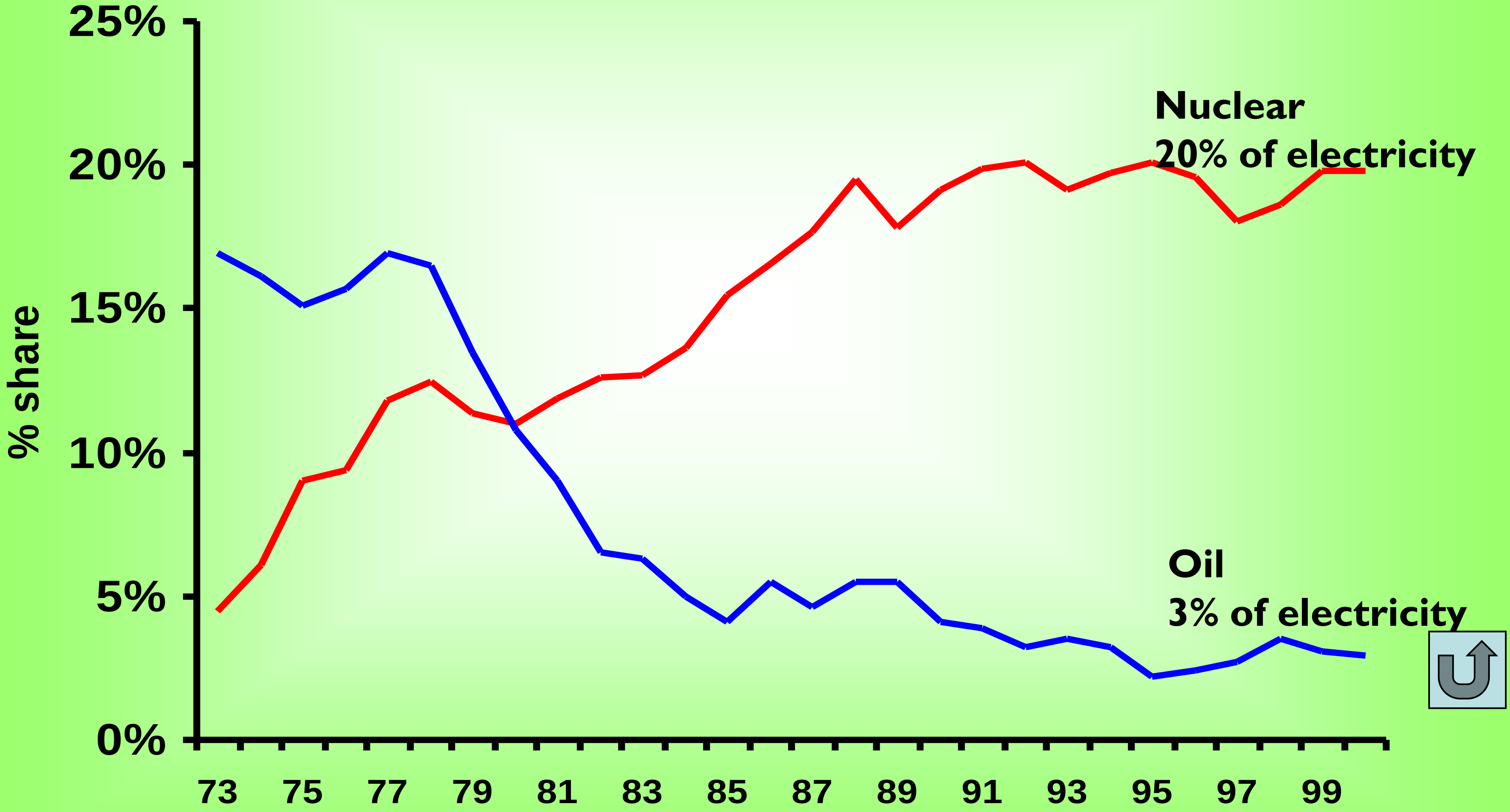
[1] Placement of an order by a utility or government agency for a nuclear steam supply system (NSSS).

Source: EIA

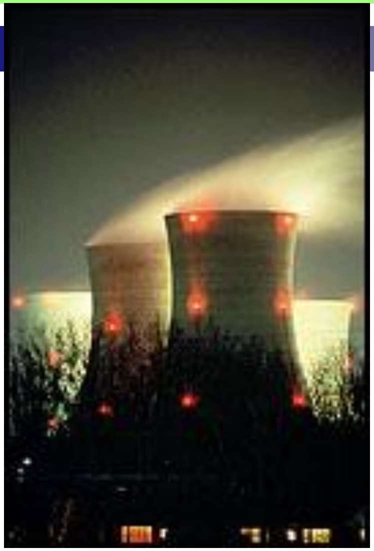
美國核能電廠取消訂購狀況

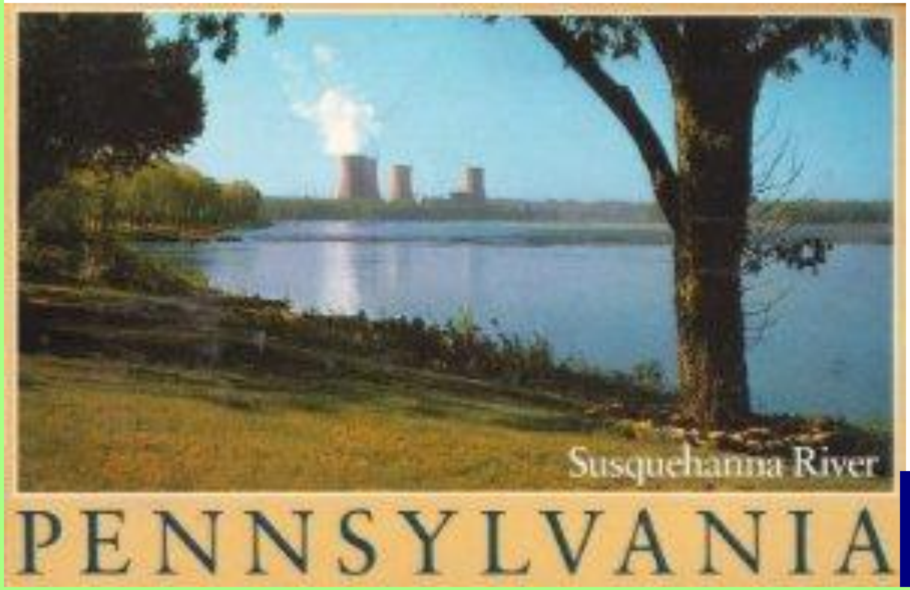


美國核能取代燃油狀況



Source: NEI

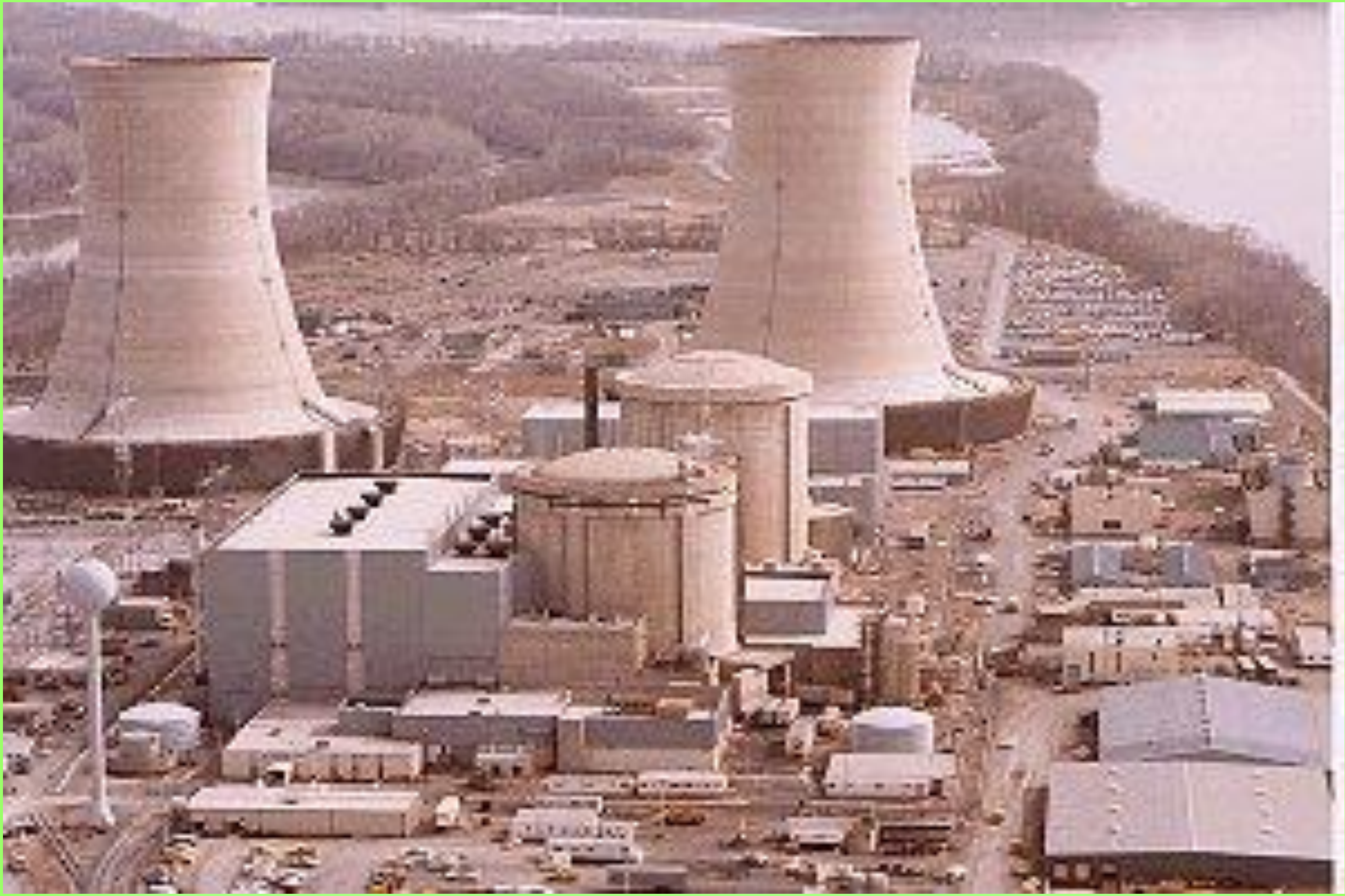




1978 Postcard, courtesy of Charles Ruggles

美國三浬島核能電廠

美國三浬島核能電廠

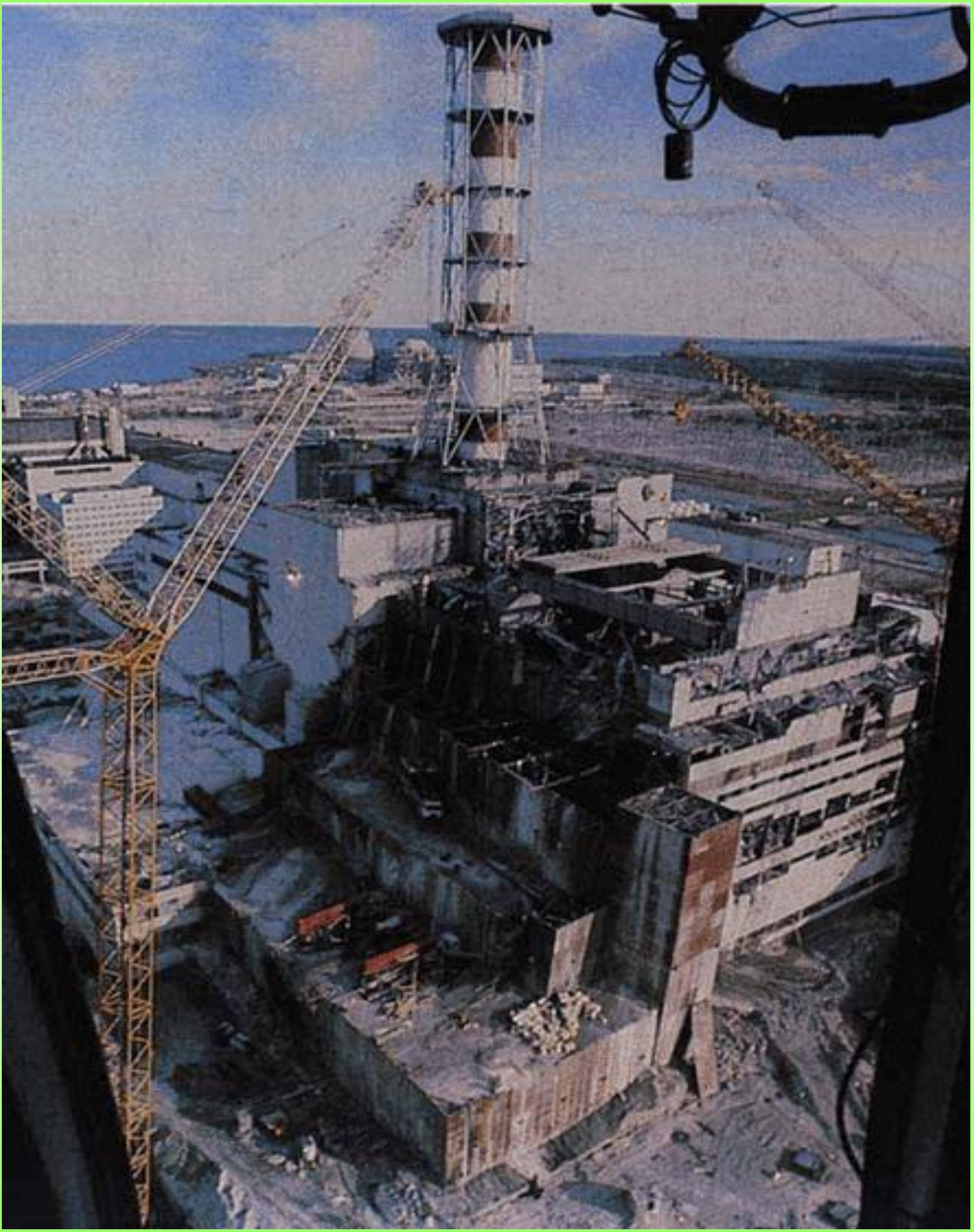


美國三浬島核能電廠

第二次石油危機

- 1974-1979，油價每桶約為12美元
- 1977，台灣石油依存度為77%，對中東依存度為92%
- 1979伊朗政變，油產停頓
- 各國搶油，油價飆到每桶30-40元
- 兩次石油危機，造成世界經濟衰退

GE



Reactor 4 Chernobyl NPS . Covered with Sarcophagus since accident in 1986.
0.96.07.02.17 DEC 1995
CHERNOBYL UKRAINE D
© Greenpeace/Shirley

日本福島核能一廠事故說明

- 地震發生後（3月11日 14:46），造成四座核電廠 11部機組跳機，控制棒成功插入爐心，終止核分裂連鎖反應
  - -- 福島核能一廠（三部運轉，三部停機維修）
  - -- 福島核能二廠（三部機）
  - -- 女川核電廠（四部機）
  - -- 東海核電廠（一部機）
- 地震造成電廠喪失廠外電源
- 緊急柴油發電機正常啟動
- 高達14公尺的海嘯，沖毀福島核能一廠的緊急柴油機的供油設備，電廠喪失全部電源 （電廠全黑事故）
- 三部跳機後的機組依靠蒸汽驅動注水設備維持爐心水位

日本福島核能一廠事故說明

- 蒸汽驅動注水設備僅能補水，無法將讓排出系統； 熱累積於圍阻體內，圍阻體壓力上升；為避免圍阻體因過壓喪失功能，須以圍阻體排氣釋出能量
- 電池電力耗盡後，注水功能完全喪失，冷卻水逐漸蒸發，水位下降，終致燃料不再為水淹蓋， 爐心裸露
- 爐心裸露後，燃料棒護套溫度上升，鋯與水蒸汽發生劇烈反應，產生氫氣；部分揮發性較高的放射性物質（銫-137, 碘-131, 惰性氣體)自燃料丸釋出，進入圍阻體
- 二號機圍阻體喪失功能，放射性物質外釋到外界環境，

  日本政府疏散電廠附近大範圍的居民

日本福島核能一廠事故

資料來源：JAIF

日本福島核能一廠

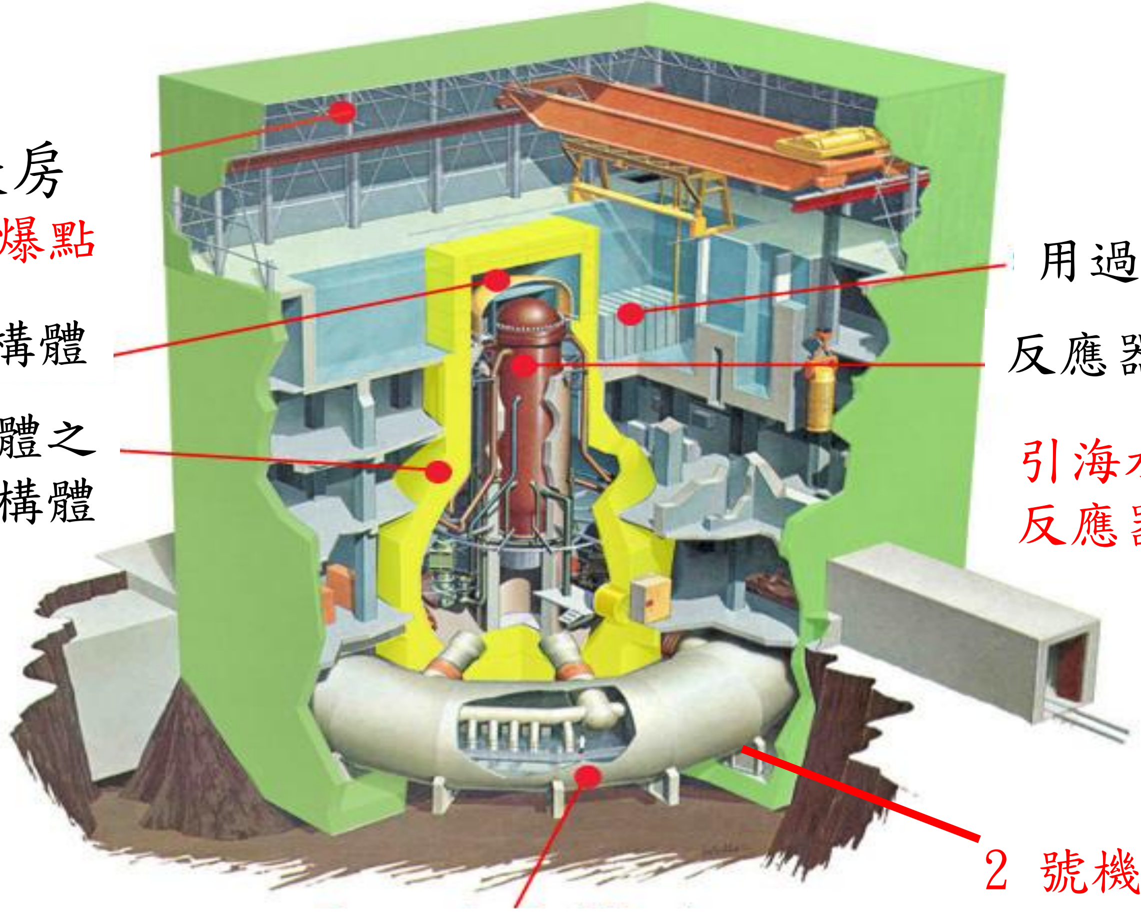
福島一廠						
機組	1號機	2號機	3號機	4號機	5號機	6號機
反應爐型式	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
裝置容量	46.0萬瓩	78.4萬瓩	78.4萬瓩	78.4萬瓩	78.4萬瓩	110.0萬瓩
商轉日期	1971. 3.26	1974 7.18	1976 3.27	1978 10.12	1978 4.18	1979 10.24
地震發生時機組狀態	正常運轉中	正常運轉中	正常運轉中	停機大修中	停機大修中	停機大修中
所在地	福島縣雙葉郡大熊町					
所有者	東京電力公司TEPCO					

日本福島核能一廠


Fukushima Dai-ichi Nuclear Power Plant
Unit 6
Unit 5
Unit 1
Unit 2
Unit 3
Unit 4

福島一廠海嘯前後空照圖

沸水式反應器第四型
馬克一號圍阻體設計



反應器廠房

1與3號機氫爆點

圍阻體鋼殼結構體

一次圍阻體之
混凝土結構體

用過燃料儲存池

反應器壓力槽

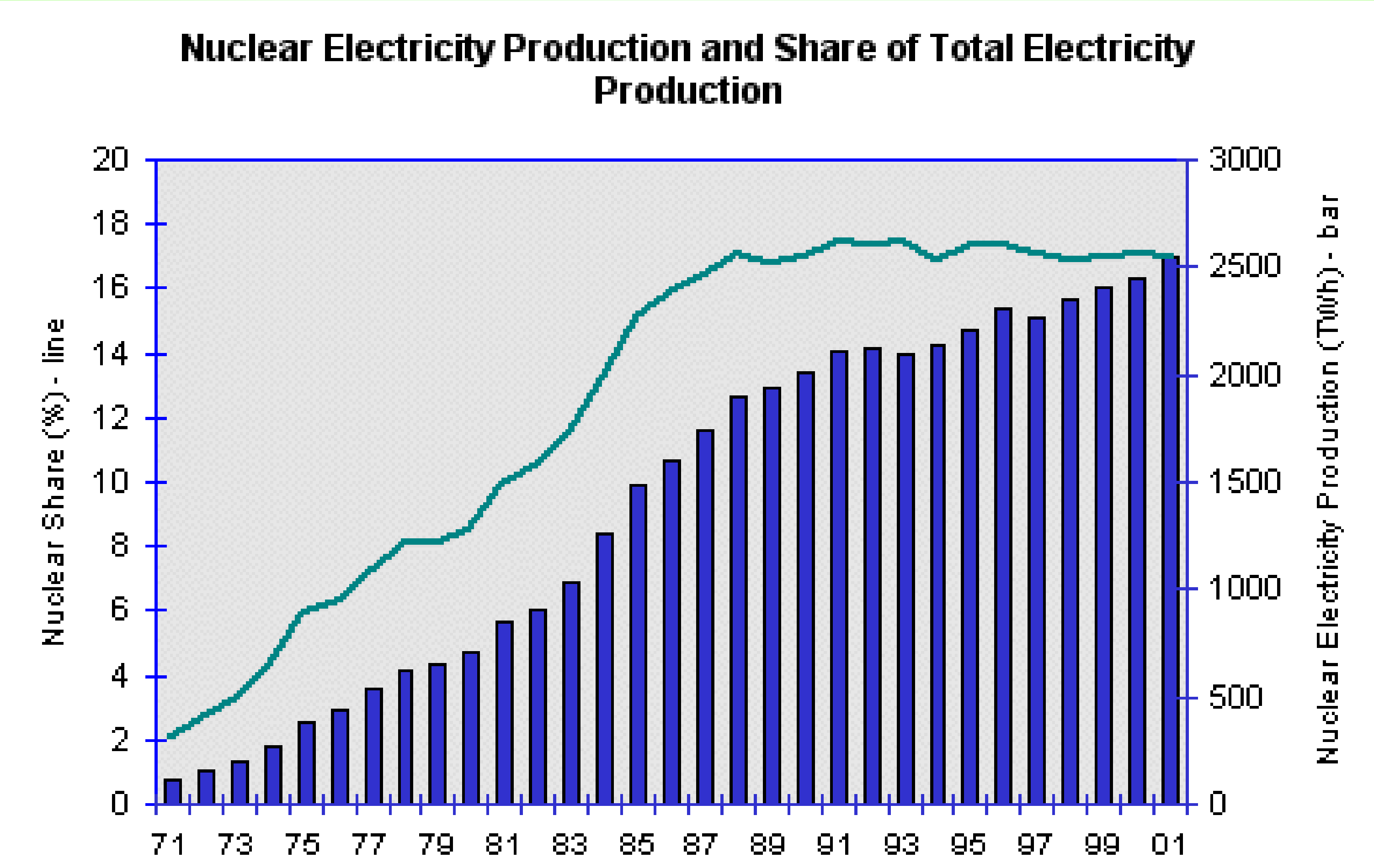
引海水灌入
反應器壓力槽

2 號機爆炸點（?）

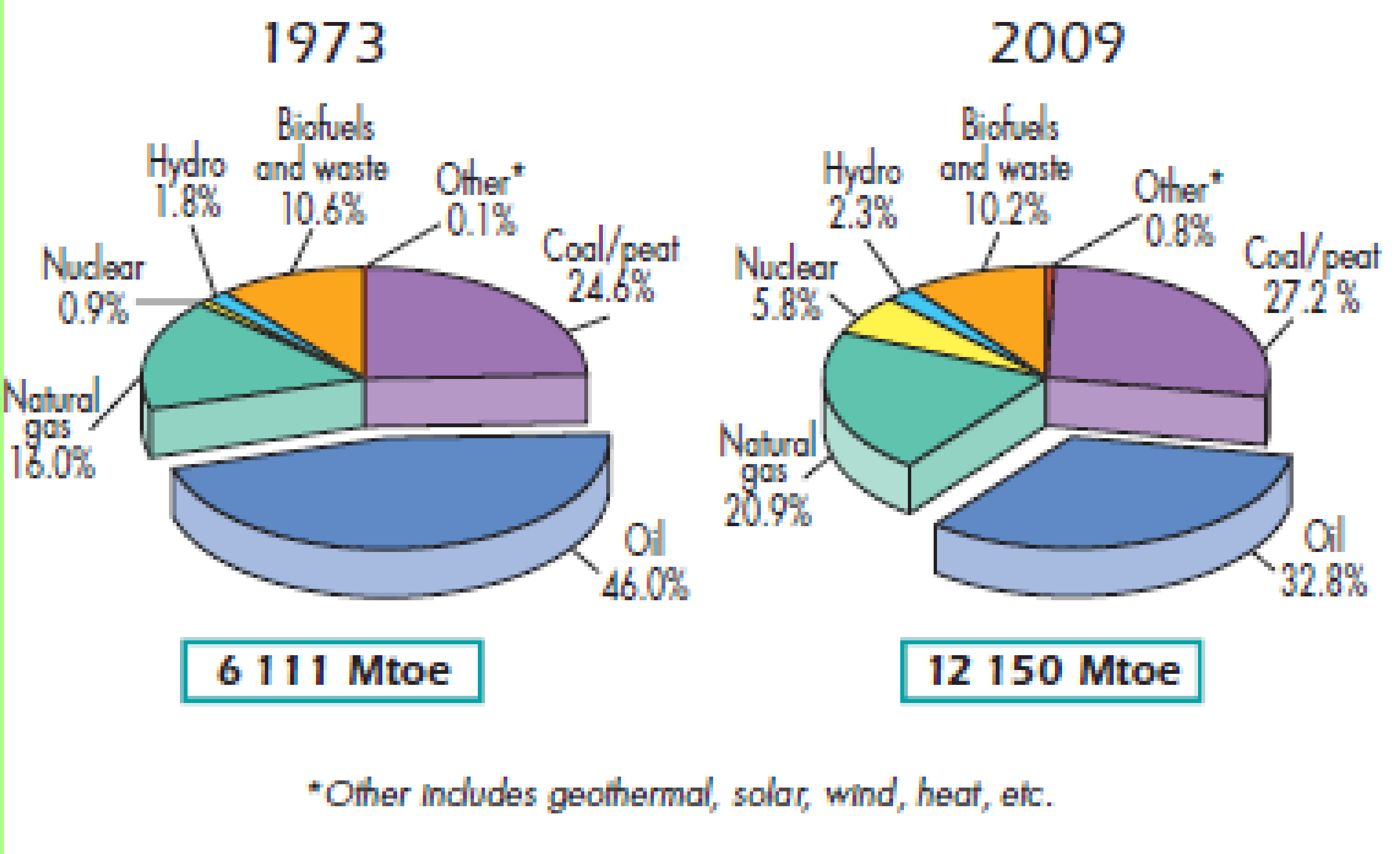
抑壓池空間

Photo taken from Nuclear Engineering Institute Webpage

全球核能增長狀況


Nuclear Electricity Production and Share of Total Electricity Production

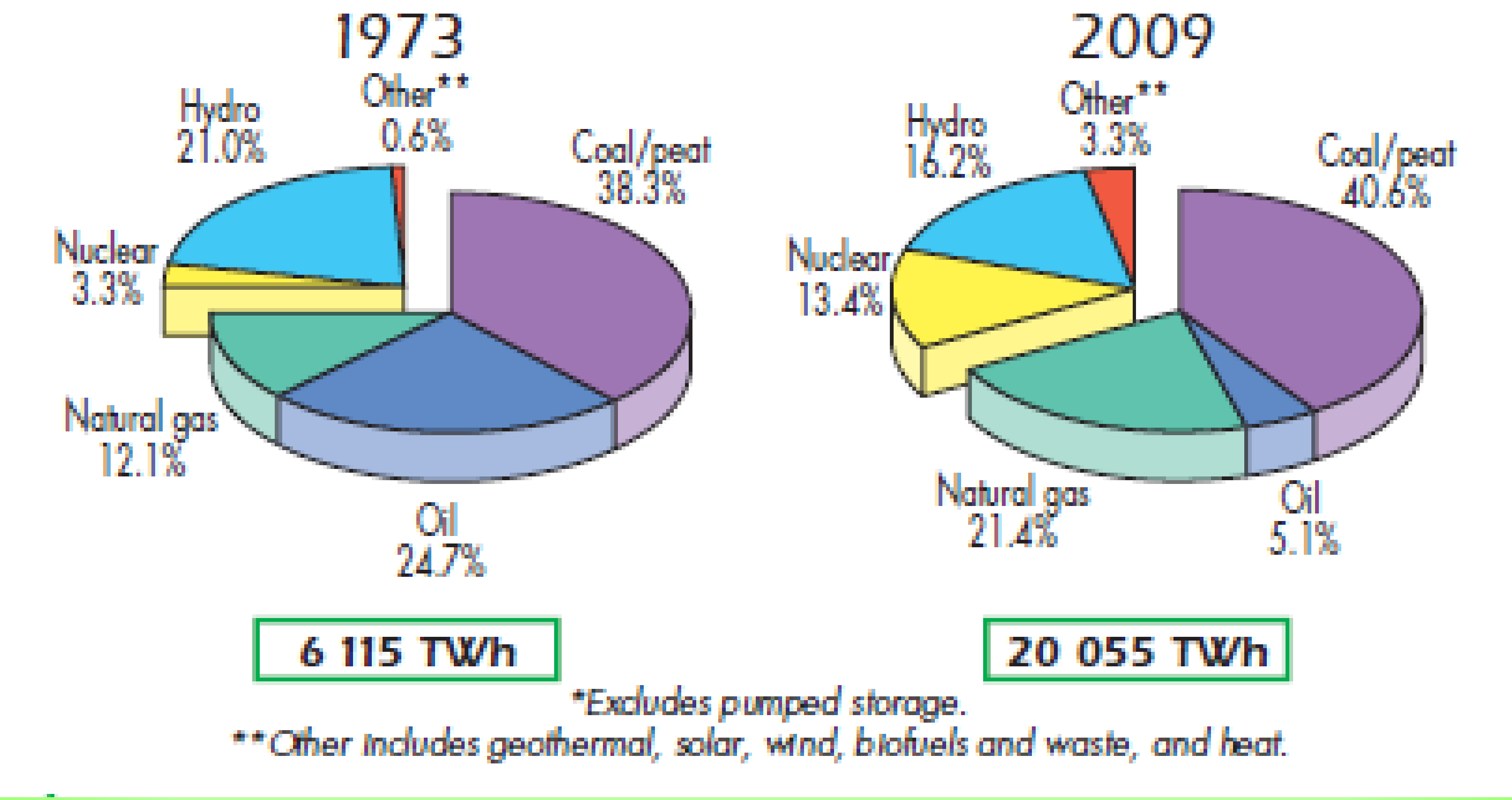
1973年, 2009 年全世界初級能源消耗（種類分佈）



Mtoe: 百萬噸油當量，4.1868 x 10 ^{13} kJ

*International Energy Agency, Key World Energy Statistics

發電使用燃料的配比



*Excludes pumped storage.

**Other includes geothermal, solar, wind, biofuels and waste, and heat.

*International Energy Agency, Key World Energy Statistics

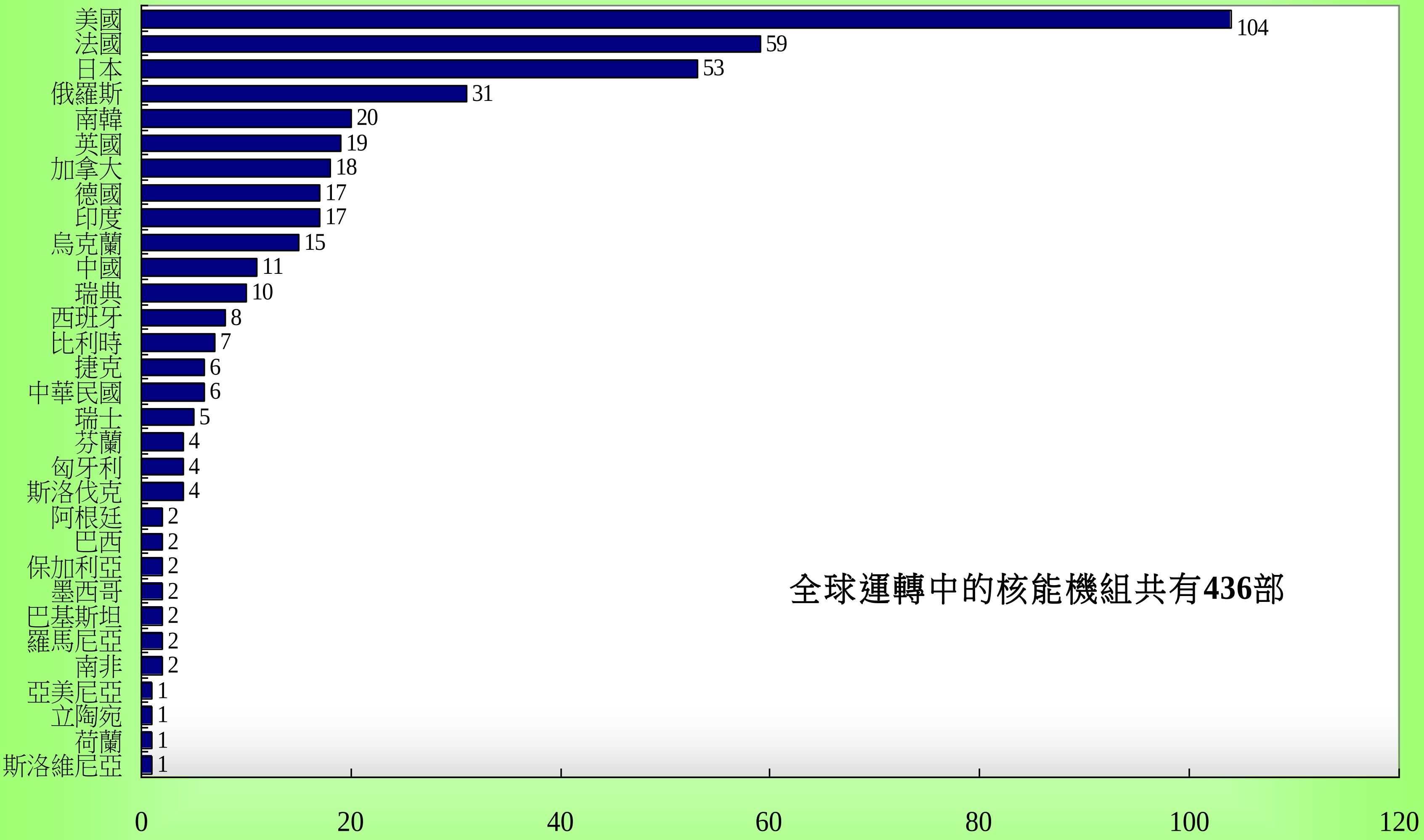
World Nuclear Power Generation and Capacity (2001)

Country	Units	Total MWe	bkWh	%
Argentina	2	935	6.5	8.0
Armenia	1	376	1.9	35.0
Belgium	7	5,712	44.1	58.0
Brazil	2	1,901	14.4	4.0
Bulgaria	6	3,538	18.2	42.0
Canada	14	10,018	72.4	13.0
China	3	2,167	16.7	1.0
Czech RP	5	2,569	14.7	20.0
Finland	4	2,656	21.9	31.0
France	59	63,003	401.3	77.0
Germany	19	21,283	162.3	31.0
Hungary	4	1,755	14.1	39.0
India	14	2,503	17.3	4.0
Japan	54	44,289	321.9	34.0
Korea RP	16	12,990	112.1	40.7
Lithuania	2	2,370	11.4	78.0

Country	**Units**	**Total MWe**	**bkWh**	**%**
Mexico	2	1,360	8.1	4.0
Netherlands	1	450	3.7	4.0
Pakistan	2	425	2.0	3.0
Romania	1	655	5.0	11.0
Russia	30	20,793	125.4	14.9
Slovak RP	6	2,408	17.1	53.0
Slovenia	1	676	5.0	39.0
South Africa	2	1,800	13.3	7.0
Spain	9	7,524	61.1	29.0
Sweden	11	9,432	69.2	44.0
Switzerland	5	3,210	25.3	36.0
Ukraine	13	11,207	71.7	46.0
UK	33	12,498	82.3	23.0
US	103	96,795	768.8	20.0
TOTAL	**431**	**348,414**	**2509.2**	**16.0**

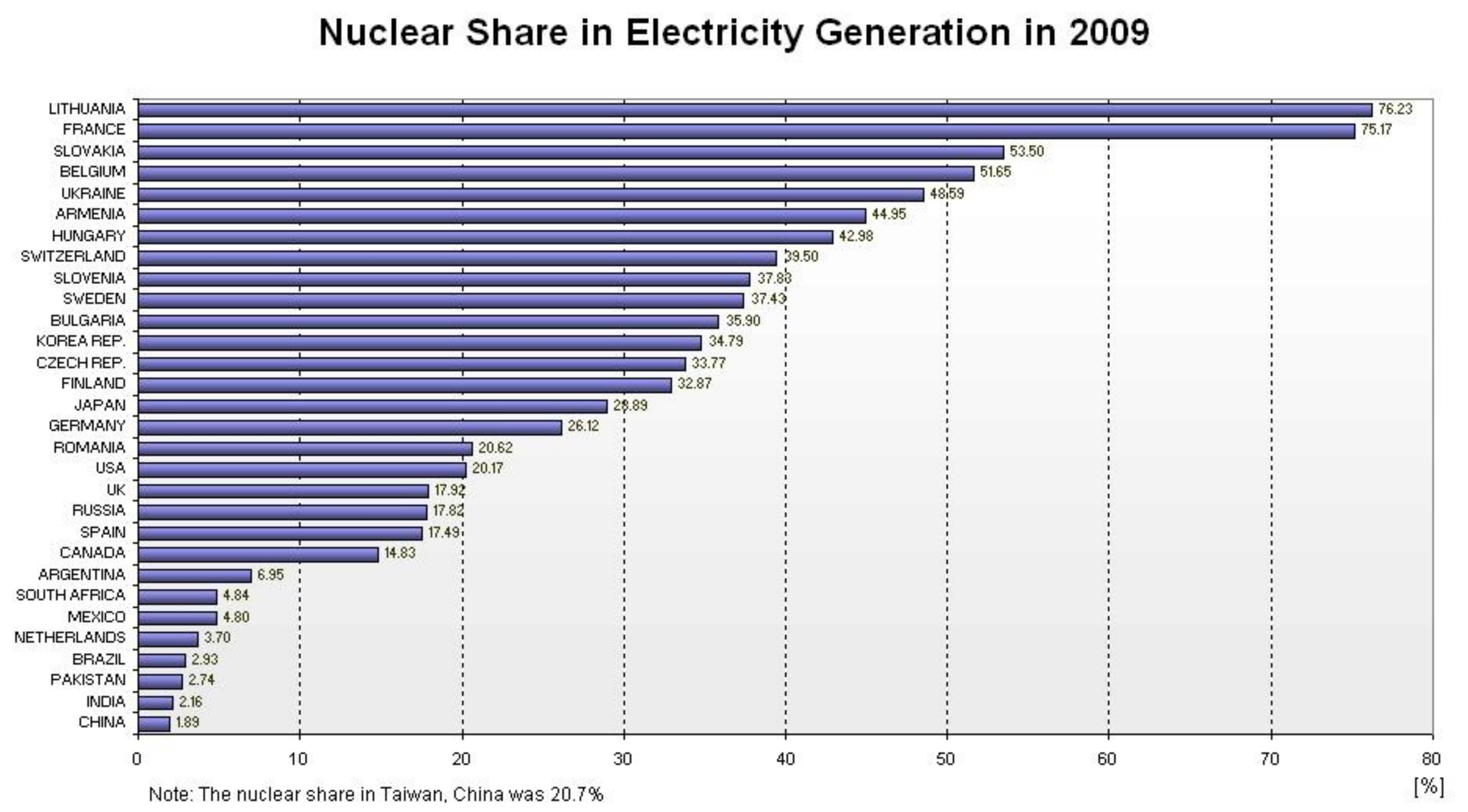
Source: International Atomic Energy Agency (IAEA)

全球運轉中的核能機組



全球運轉中的核能機組共有**436**部

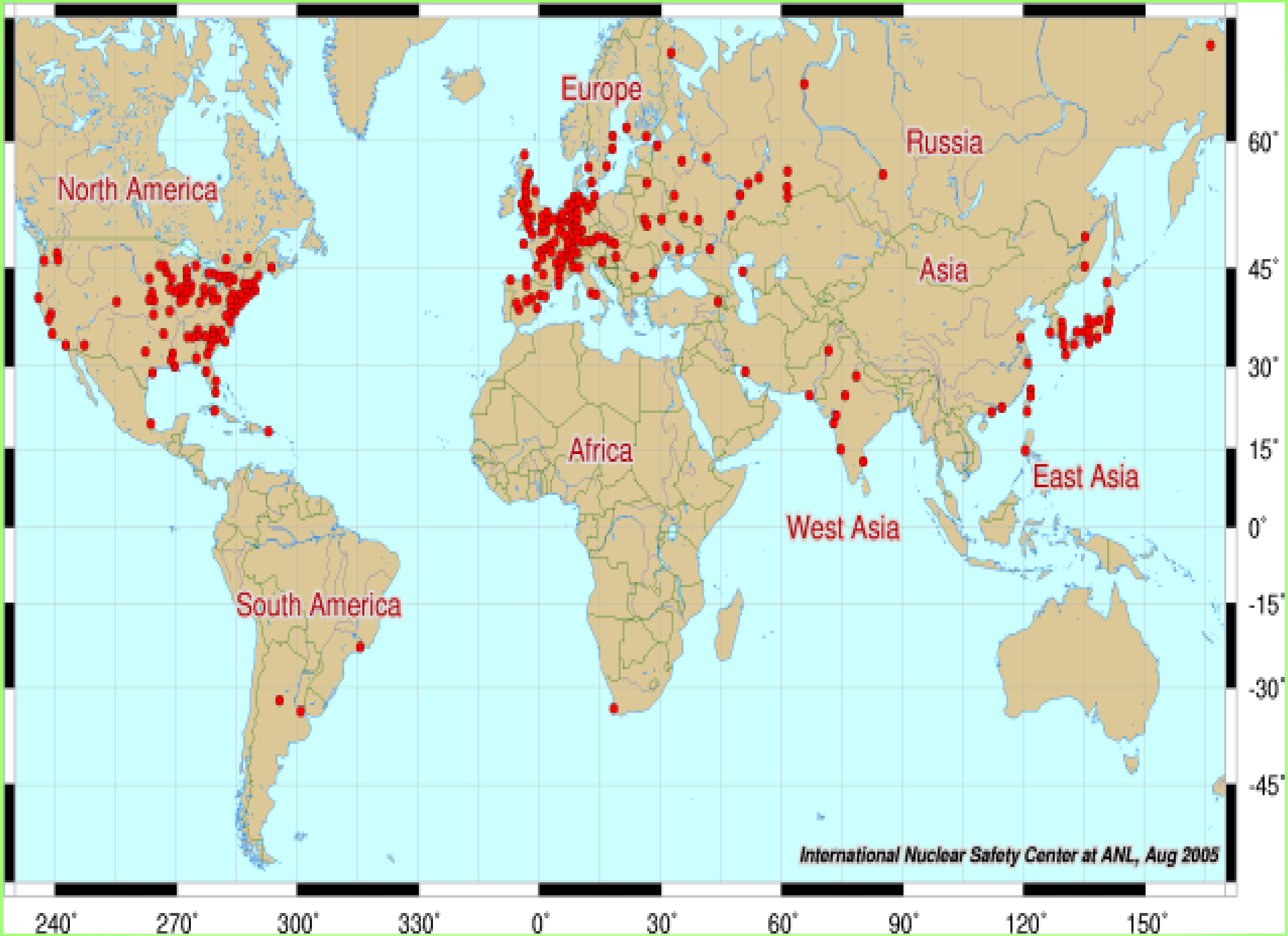
資料來源：國際原子能總署(2009年2月更新)



Nuclear Share in Electricity Generation in 2009

Note: The nuclear share in Taiwan, China was 20.7%

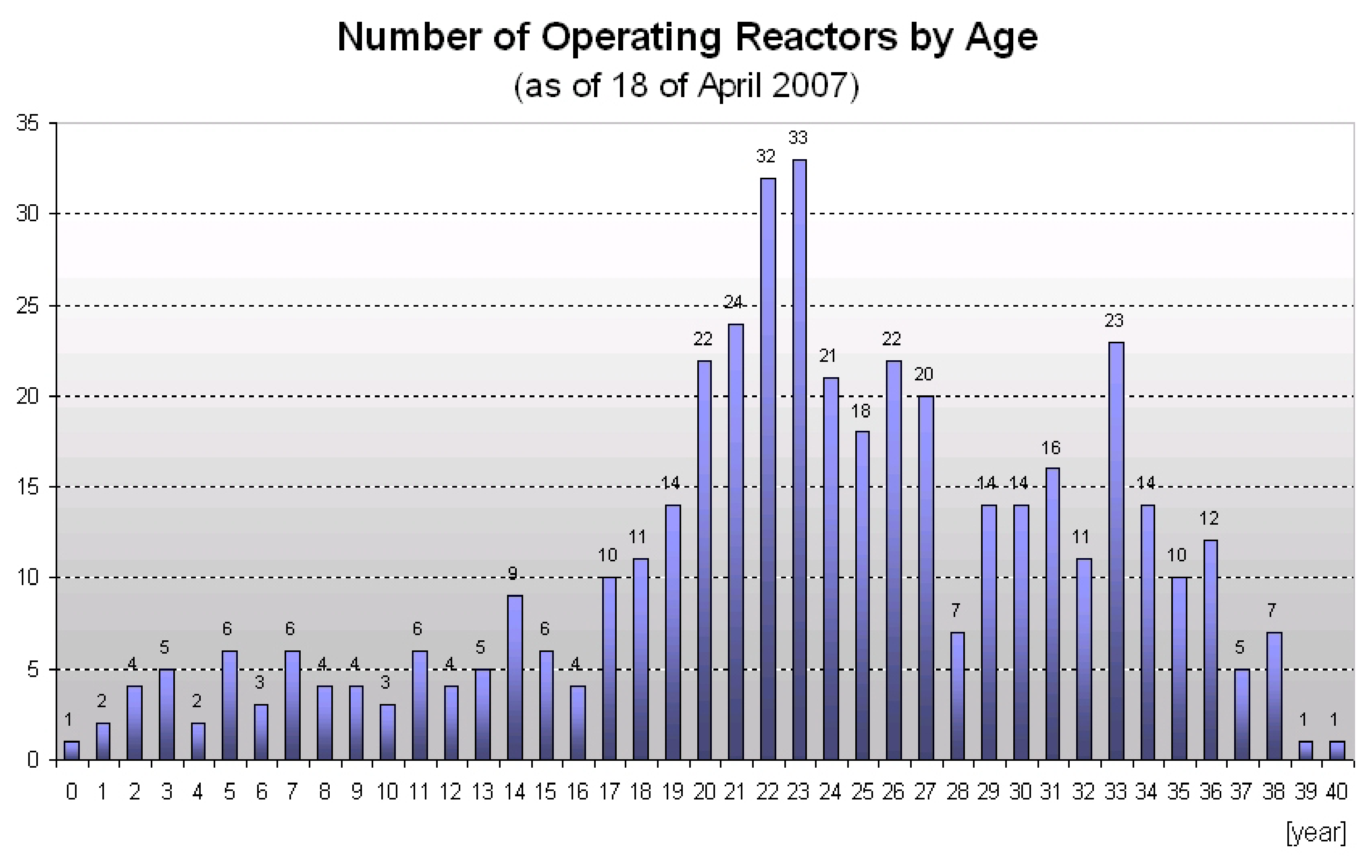
http://www.nucleartourist.com/



International Nuclear Safety Center at ANL, Aug 2005

Location of Nuclear Power Plant Around the World

http://www.nucleartourist.com/



Number of Operating Reactors by Age

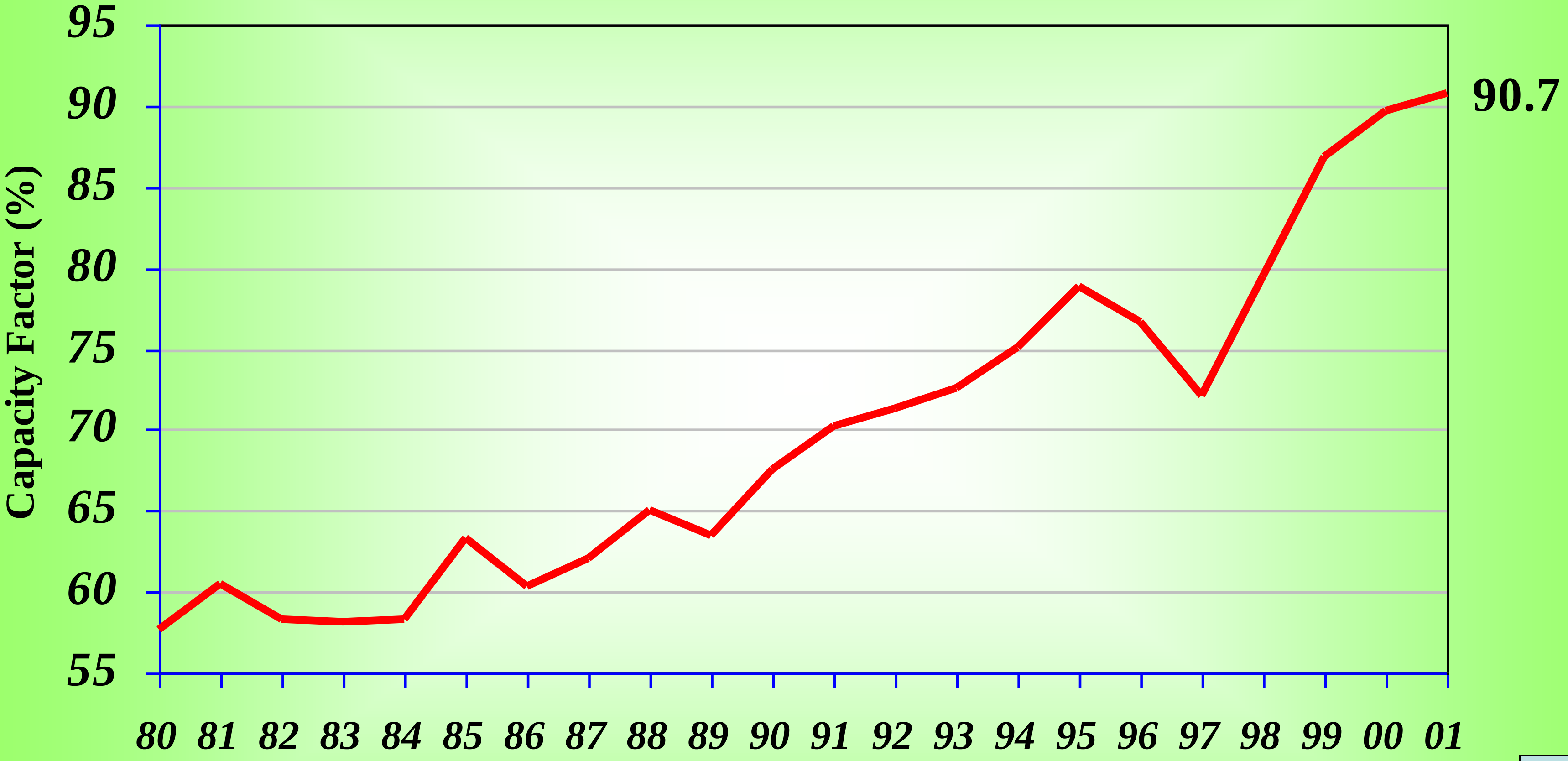
(as of 18 of April 2007)

http://www.nucleartourist.com/

各國核能電廠興建狀況

Country	**Units**	**Total MWe**
Argentina	1	692
China	8	6,426
India	2	980
Czech RP	1	912
Iran	2	2,111
Japan	3	3,696
Korea RP	4	3,820
Romania	1	650
Russia	2	1,875
Slovak RP	2	776
Taiwan	2	2,700
Ukraine	4	3,800
TOTAL	**32**	**28,438**

美國核能電廠容量因素



電廠容量因素=電廠全年實際發電量/ 電廠全年額定發電量

台灣能源供應

能源消耗為全球之1%

電力消耗為全球之1.3%

人均電力消耗：9,550 度
世界平均值的 3.7 倍

人口佔世界之 0.3%

土地面積為世界之 0.06%

超過99%的能源依賴進口

核一廠	沸水式反應器	636 MWe x 2	台北縣	1977
核二廠	沸水式反應器	985 MWe x 2	台北縣	1981
核三廠	壓水式反應器	951 MWe x 2	屏東縣	1977
核四廠	進步型沸水式反應器	1350 MWe x 2	台北縣	

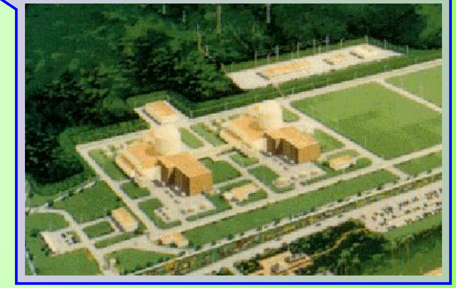
台電核能電廠分佈圖

(BWR - 636 MWe × 2)

核一廠

(ABWR - 1,350 MWe × 2)

核四廠



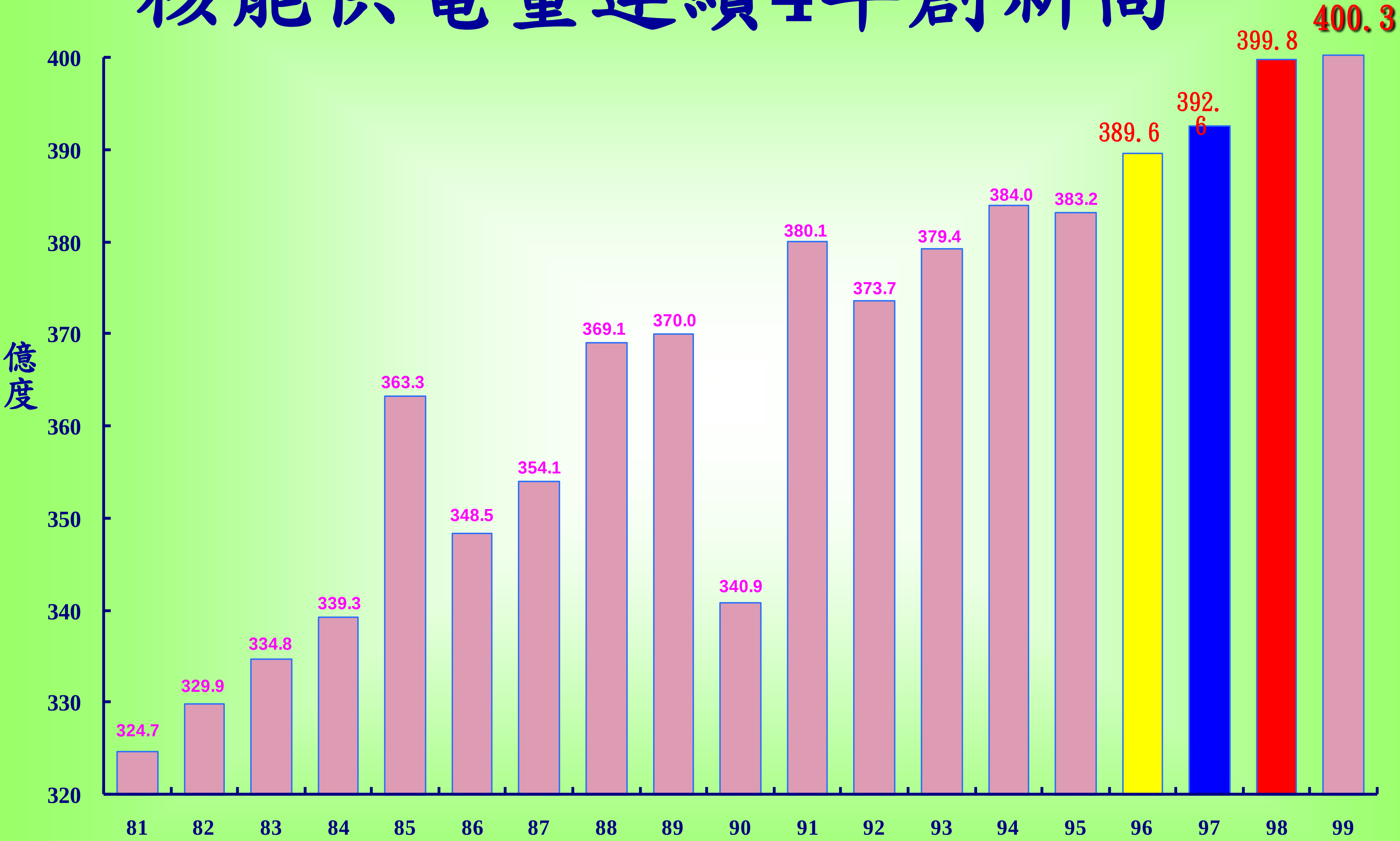
(PWR - 951 MWe × 2)

核三廠

（BWR － 985 MWe × 2）

核二廠

核能供電量連續4年創新高



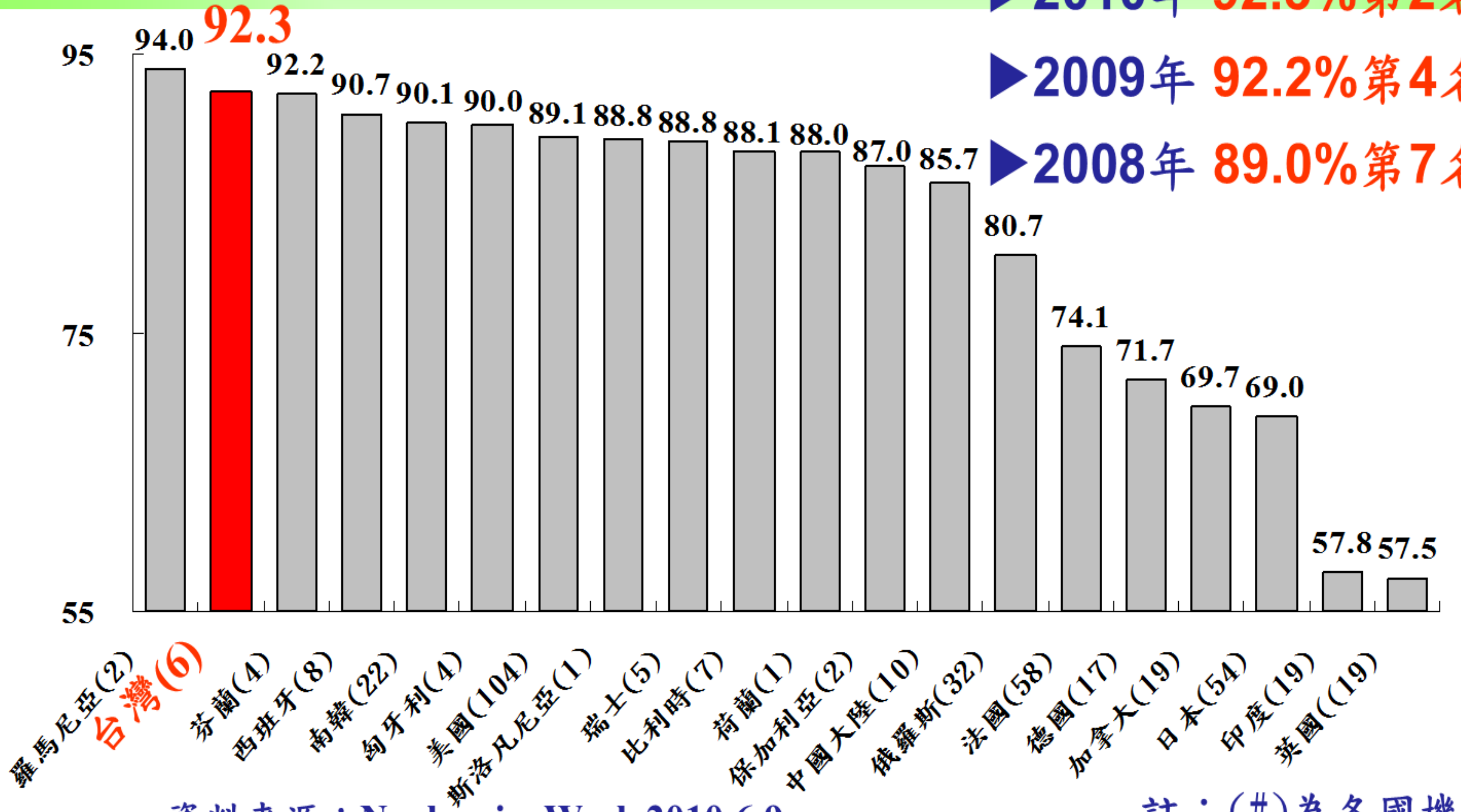
-86-

-86-

營運績效卓越

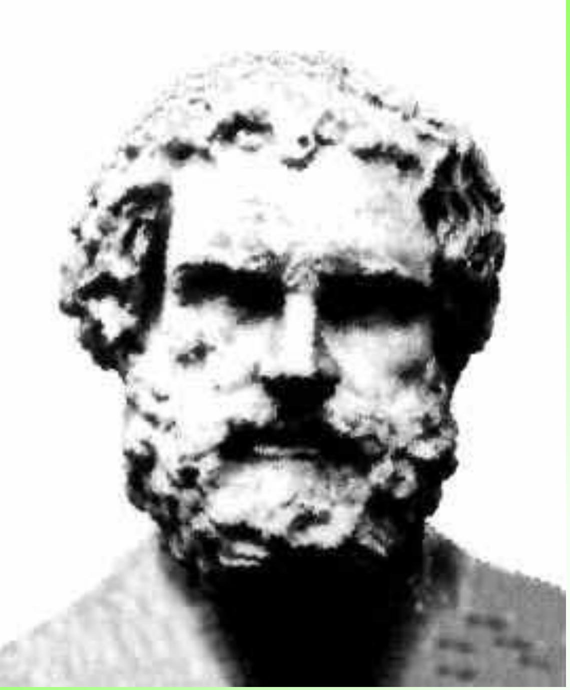
▶ 發電績效(容量因數)名列前茅

- ▶2010年 92.3%第2名
- ▶2009年 92.2%第4名(NEI)
- ▶2008年 89.0%第7名(NEI)



資料來源：Nucleonics Week 2010.6.9

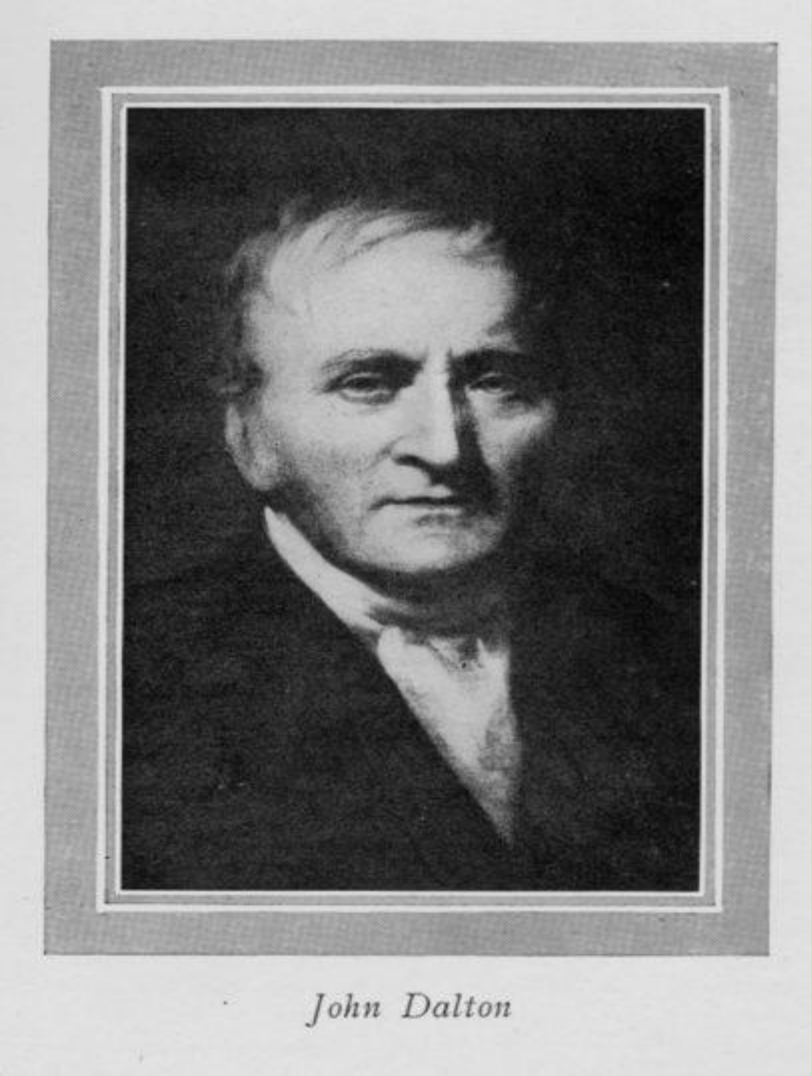
註：(#)為各國機組數



Name:	Democritus 德謨克利特
Birth:	ca. 450 BC
Death:	ca. 370 BC
School/tradition:	pre-Socratic Philosophy
Main interests:	metaphysics / physics
Notable ideas:	Atomism

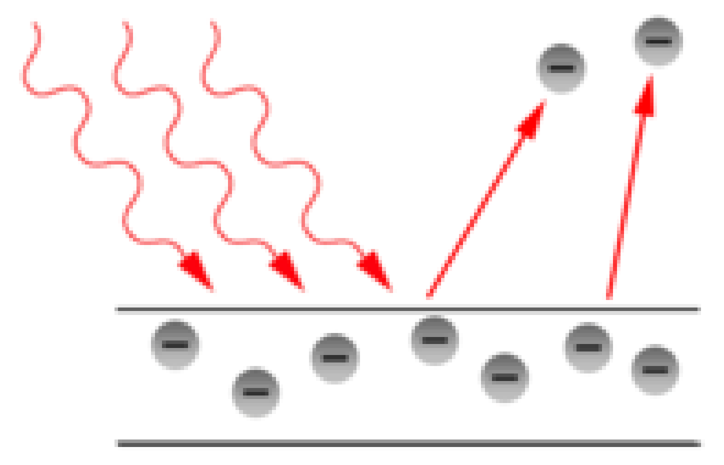
Stamp issued by Greece on Sept. 26, 1983 to honor an International Conference on Democritus and his work

http://en.wikipedia.org/wiki/Democritus



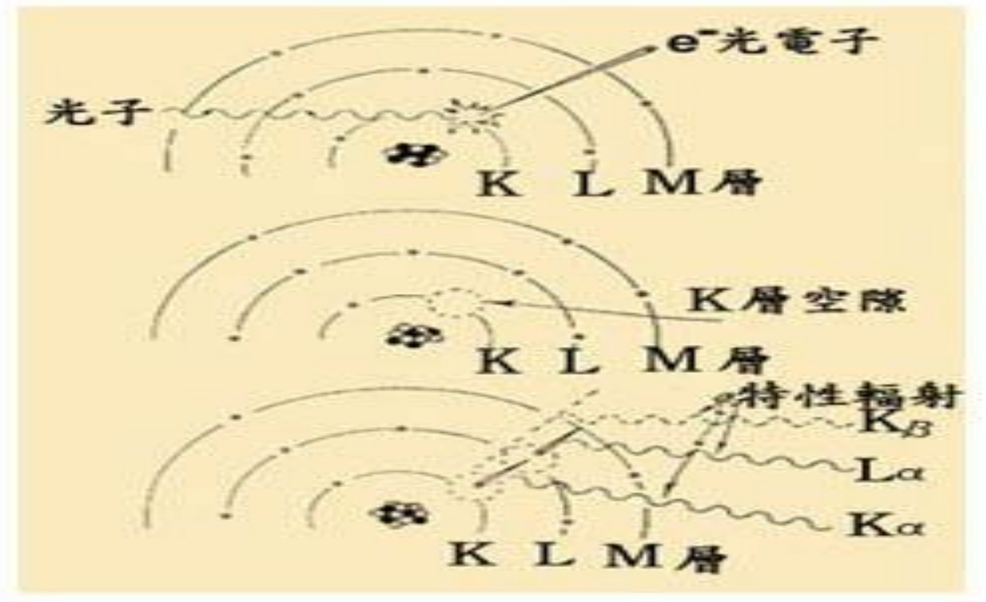
John Dalton

John Dalton (1766~1844),
English chemist and physicist



The photoelectric effect. Incoming EM radiation on the left ejects electrons, depicted as flying off to the right, from a substance.

Ultraviolet Light ~ 10^6/sec



光電效應示意圖

Heinrich Rudolf Hertz

Born:	February 22, 1857 Hamburg, Germany
Died:	January 1, 1894 Bonn, Germany
Occupation:	Physicist and mechanician

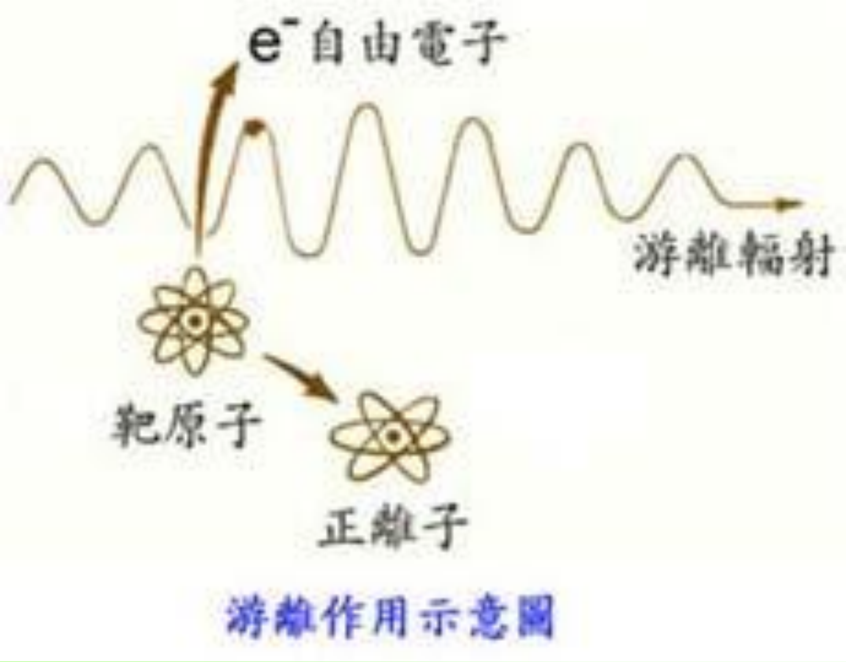
the first to demonstrate the existence of electromagnetic radiation

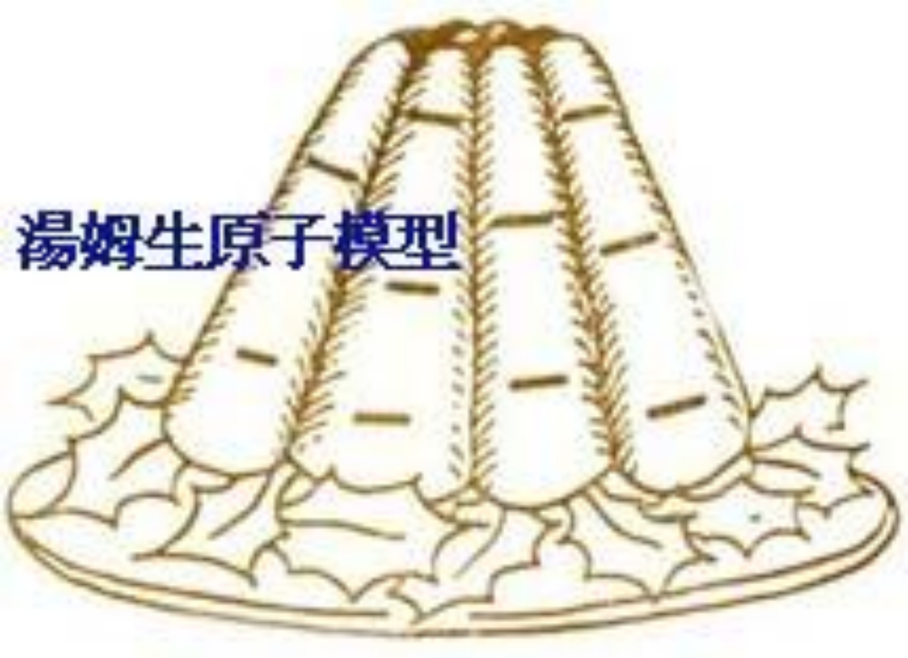
“I do not think that the wireless waves I have discovered will have any practical application”

湯姆生約於1895年攝於
英國剑橋大學卡文的斯實验室

Sir Joseph John Thomson, (1856–1940) often known as **J. J. Thomson**, was an English physicist and the discoverer of the electron.

因電子和氣體導電兩方面的卓越成就，獲得1906年諾貝爾物理獎。





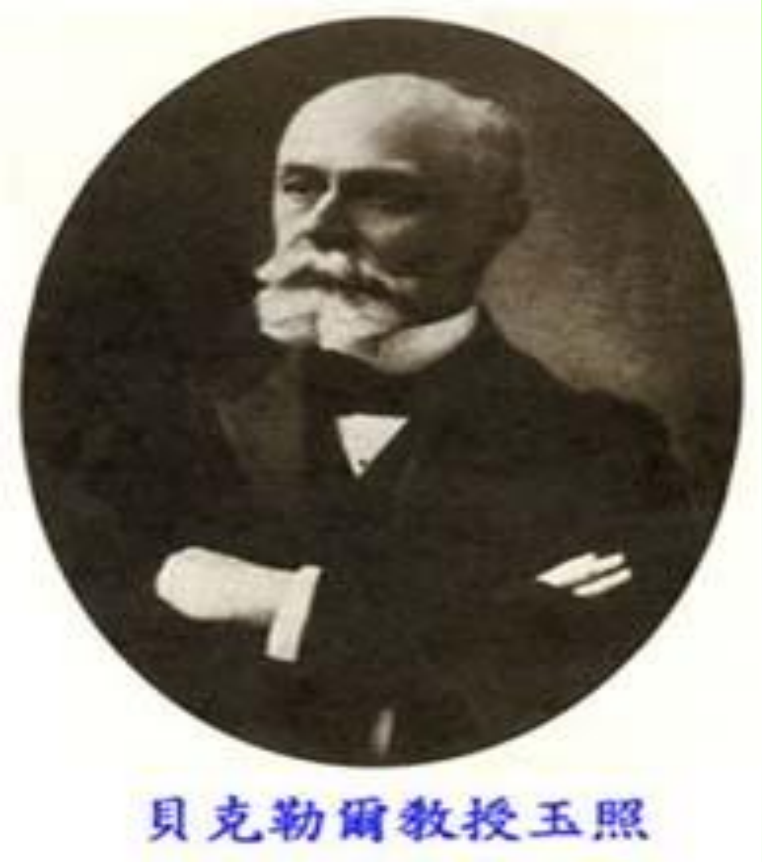
Thomson 和他的學生 Rutherford 是最早證實空氣被X射線游離。
從這游離現象推導出游離輻射 (放射線)，也就是由原子
釋出能量範圍廣大的電磁波和粒子輻射。

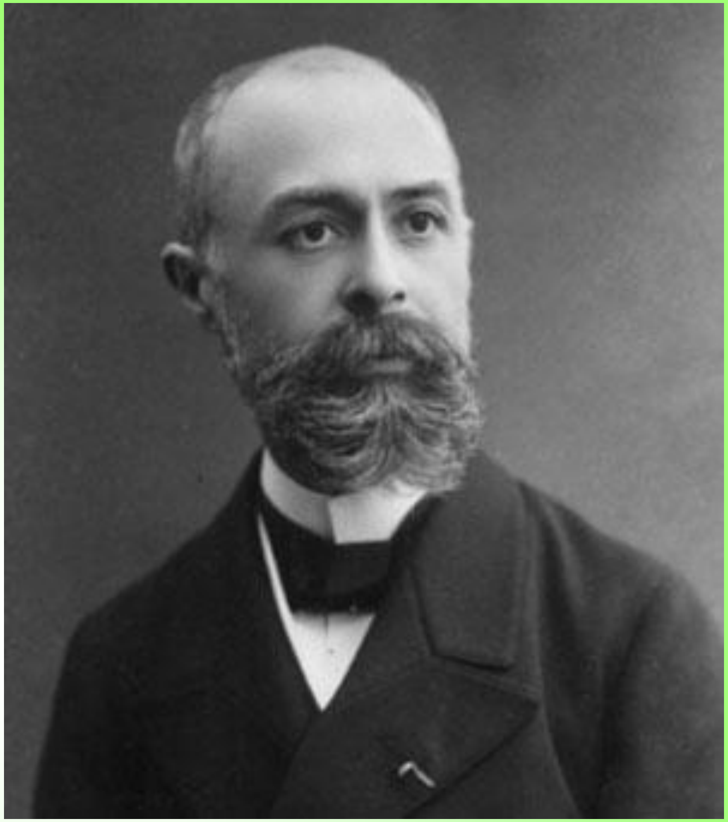
Wilhelm Röntgen

Born	March 27, 1845 Leanne, Prussia
Died	February 10, 1923 Munich, Germany

In 1901 Röntgen was awarded the very first Nobel Prize in Physics. The award was officially, *"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him"*.

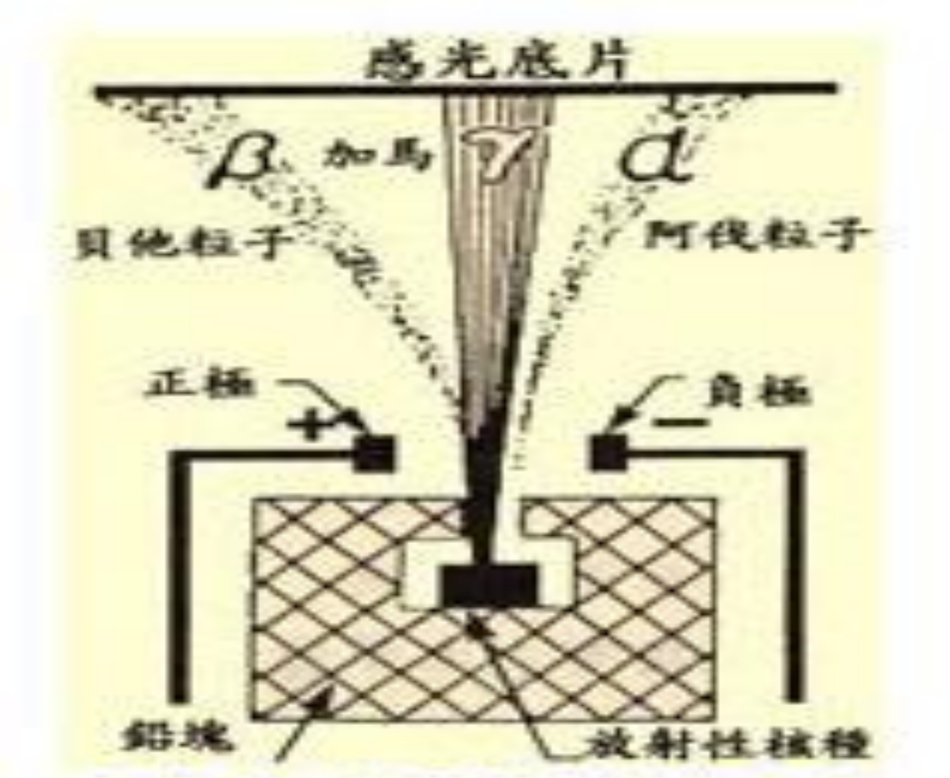
An X-ray picture (radiograph) taken by Röntgen of Albert von Kölliker's hand





Antoine Henri Becquerel (1852 - 1908) was a French physicist, Nobel laureate (1903), and one of the discoverers of radioactivity.

其名字「貝克」為輻射度量的活性單位。



現今多用電場偏轉阿伐和貝他粒子

Marie Curie (**Maria Skłodowska-Curie**, 1867~1934)
Polish – French physicist and Chemist.

Nobel Physics Prize, 1903
Nobel Chemistry Prize, 1911

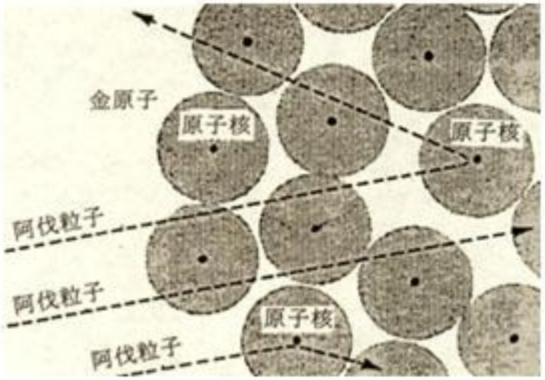
Pierre Curie (1859 ~ 1906),
French physicist

Nobel Physics Prize, 1903

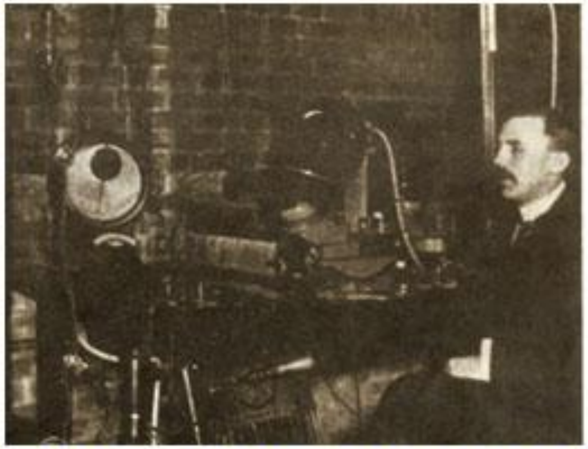
Ernest Rutherford, (1871 ~ 1937)
nuclear physicist from New Zealand
the "father" of nuclear physics
Pioneered the orbital theory of the atom

1908 Nobel Prize in Chemistry

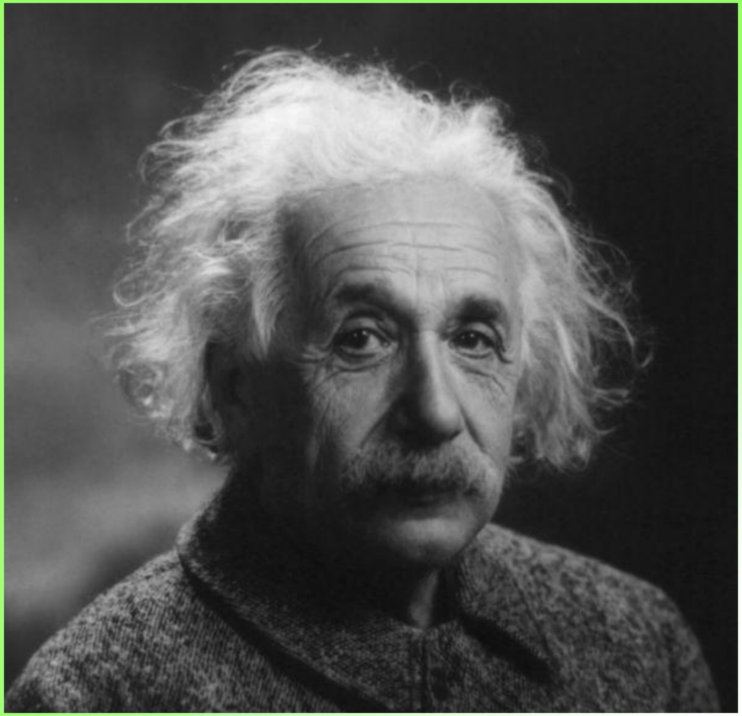
鈾和釷會變成不同的元素，也就是「轉變」



拉塞福聞名的阿伐粒子散射實驗



拉塞福約於1903年攝於加拿大麥基爾大學

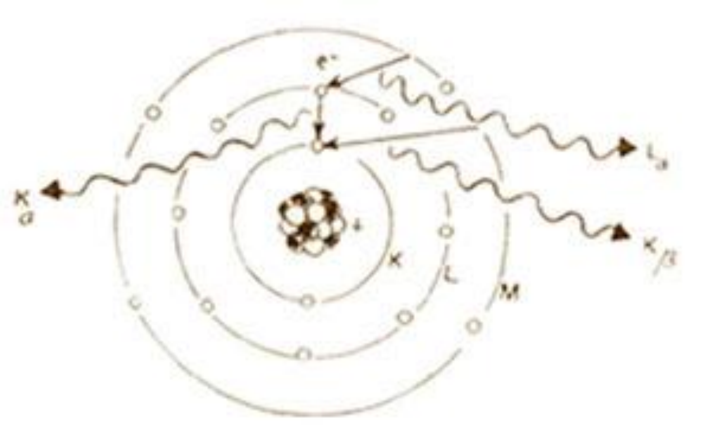


Albert Einstein (1879 ~ 1955)
German-born theoretical physicist.
widely regarded as the most important scientist of the 20th century and
one of the greatest physicists of all time

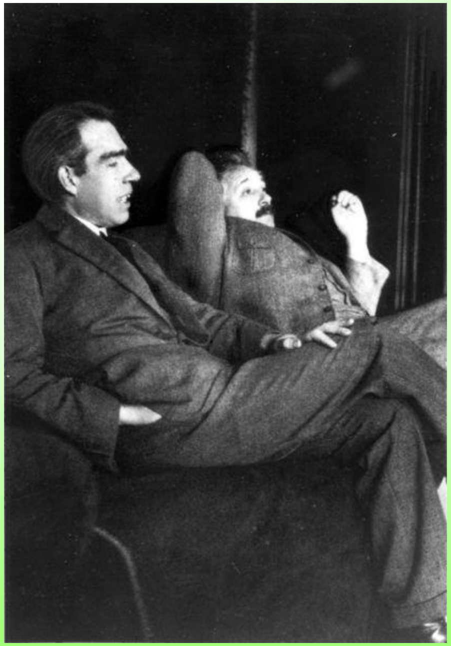
1921 Nobel Prize for Physics for the explanation of the photoelectric effect in 1905

Niels Bohr (1885 ~ 1962), Danish chemist
contributions to understanding
atomic structure and quantum mechanics

1922 Nobel Prize for Physics



電子自L層殼躍遷至K層殼時
發出電磁輻射Kα



Einstein and
Niels Bohr

Walther Wilhelm Georg Bothe (1891 ~ 1957)
German physicist, mathematician, chemist

1954 Nobel Prize in Physics (along with Max Born)
for the invention of the coincidence circuit

Frédéric Joliot-Curie (1900 ~ 1958)
French physicist

Irène Joliot-Curie (1897~1956)
French-Polish scientist

1935 the Nobel Prize for Chemistry
for their discovery of artificial radioactivity

Sir James Chadwick (1891~1974)
English physicist

1935 the Nobel Prize for Physics

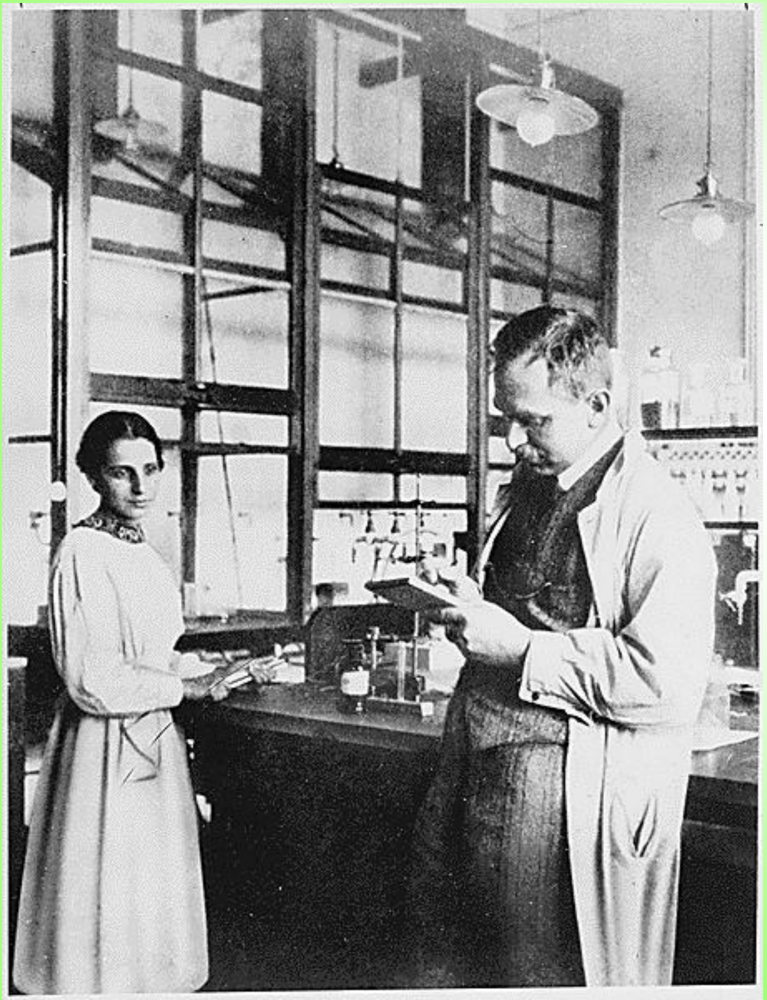
Enrico Fermi (1901~1954),Italian physicist
most noted for his work on beta decay,
the development of the first nuclear reactor,
and for the development of quantum theory

1938 Nobel Prize in Physics
for the work on induced radioactivity

Leó Szilárd (1898~1964), Hungarian-American physicist conceived the nuclear chain reaction and worked on the Manhattan Project.

Fritz Strassman (1902 ~ 1980), German chemist

Otto Hahn (1879 ~ 1968), German chemist
1944 Nobel Prize in Chemistry



Meitner and Hahn working together at the Kaiser Wilhelm Institute

Lise Meitner (1878~1968)

Austrian physicist

1900

1926

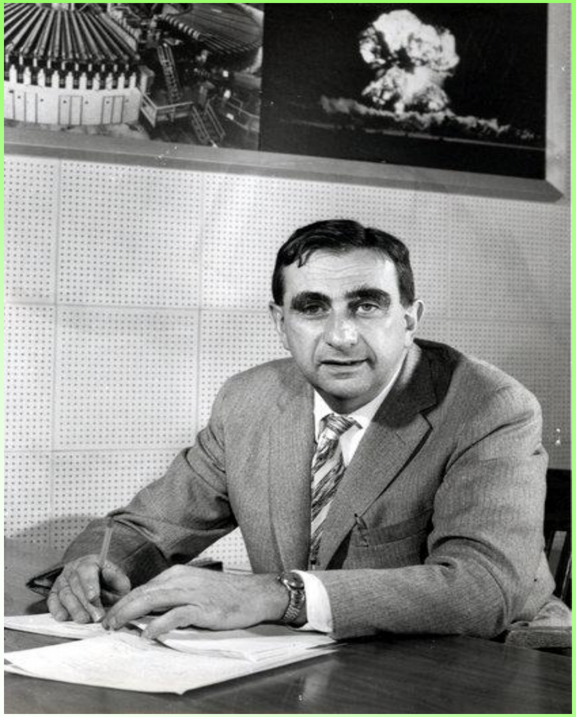
Werner Karl Heisenberg (1901~1976), German physicist

1932 Nobel Prize in physics

Heisenberg uncertainty principle

Eugene Paul Wigner (1902~1995),
Hungarian physicist and mathematician

1963 Nobel Prize in Physics



Edward Teller (1908~2003),
Hungarian-born American nuclear physicist
known colloquially as
"the father of the hydrogen bomb"

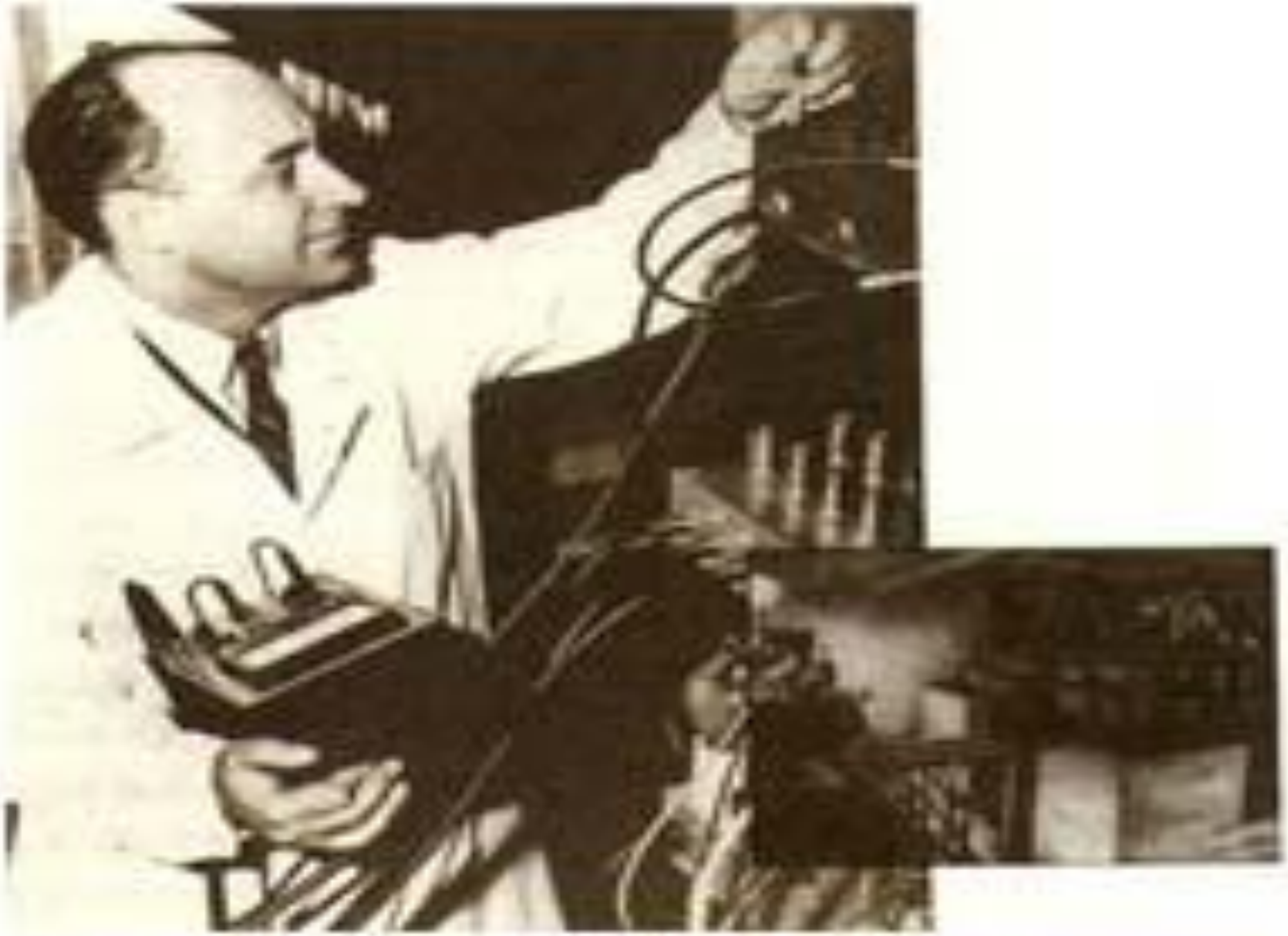
Teller became a major lobbying force of the Strategic Defense Initiative to President Ronald Reagan in the 1980s.

Glenn Theodore Seaborg (1912~1999), American chemist

1951 Nobel Prize in Chemistry

prominent in the discovery and isolation of ten transuranic elements

Ernest O. Lawrence, Glenn Seaborg and Robert Oppenheimer at the controls of the 187-inch cyclotron



費米攝於芝加哥大學CP-1反應堆

J. Robert Oppenheimer (1904~1967),
American theoretical physicist,
best known for his role as
the scientific director
of the Manhattan Project

“ the father of the atomic bomb "

Military head: General Leslie Groves
scientific director: Robert Oppenheimer

J. Robert Oppenheimer and General Leslie Groves at the Trinity test site. Metal rods are all that remain of the 100-foot tower on which the first nuclear device exploded. (Los Alamos National Laboratory)

Robert J. Oppenheimer

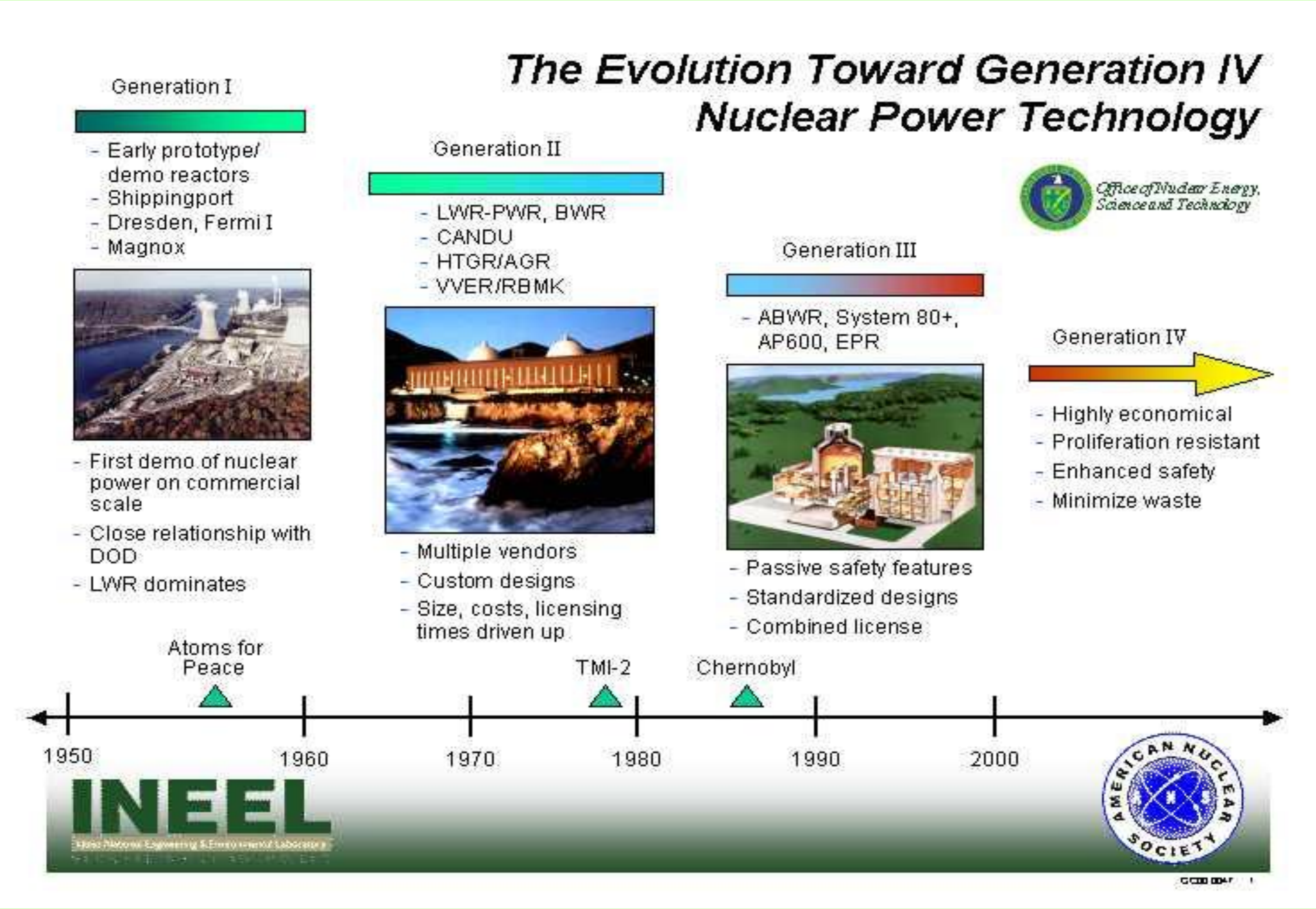
A group of physicists at a wartime Los Alamos colloquium

A selection of U.S. sites important to the Manhattan Project

Ernest Orlando Lawrence (1901~1958),
American physicist

1939,Nobel Prize in Physics for his work on the cyclotron and its applications

work in uranium-isotope separation in the Manhattan Project



The Evolution Toward Generation IV Nuclear Power Technology

Office of Nuclear Energy, Science and Technology

Generation I

- Early prototype/ demo reactors
- Shippingport
- Dresden, Fermi I
- Magnox

- First demo of nuclear power on commercial scale
- Close relationship with DOD
- LWR dominates

Generation II

- LWR-PWR, BWR
- CANDU
- HTGR/AGR
- VVER/RBMK

- Multiple vendors
- Custom designs
- Size, costs, licensing times driven up

Generation III

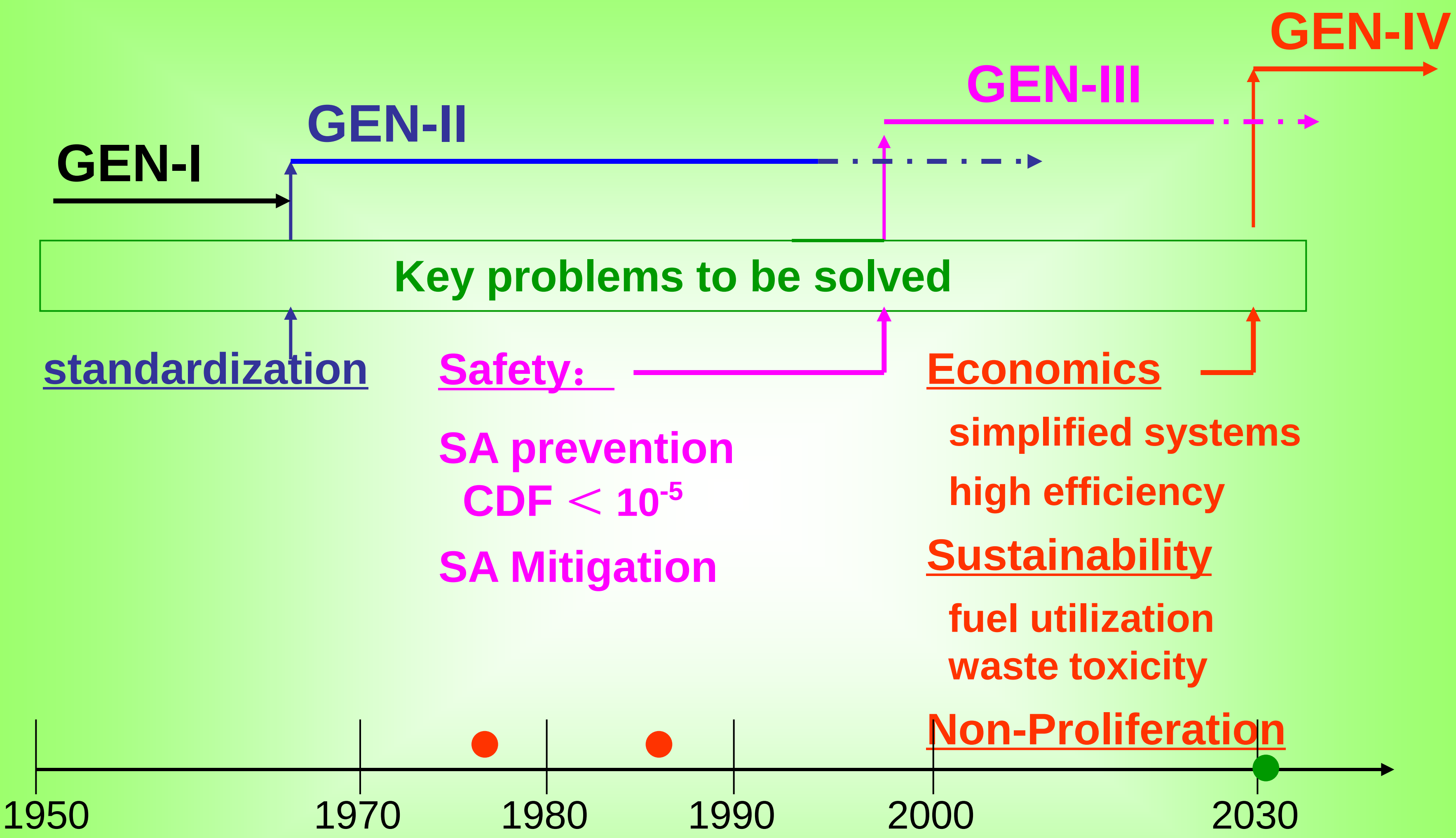
- ABWR, System 80+, AP600, EPR

- Passive safety features
- Standardized designs
- Combined license

Generation IV

- Highly economical
- Proliferation resistant
- Enhanced safety
- Minimize waste

INEEL



GEN-I

GEN-II

GEN-III

GEN-IV

Key problems to be solved

standardization

Safety:

SA prevention
CDF < 10^{-5}

SA Mitigation

Economics

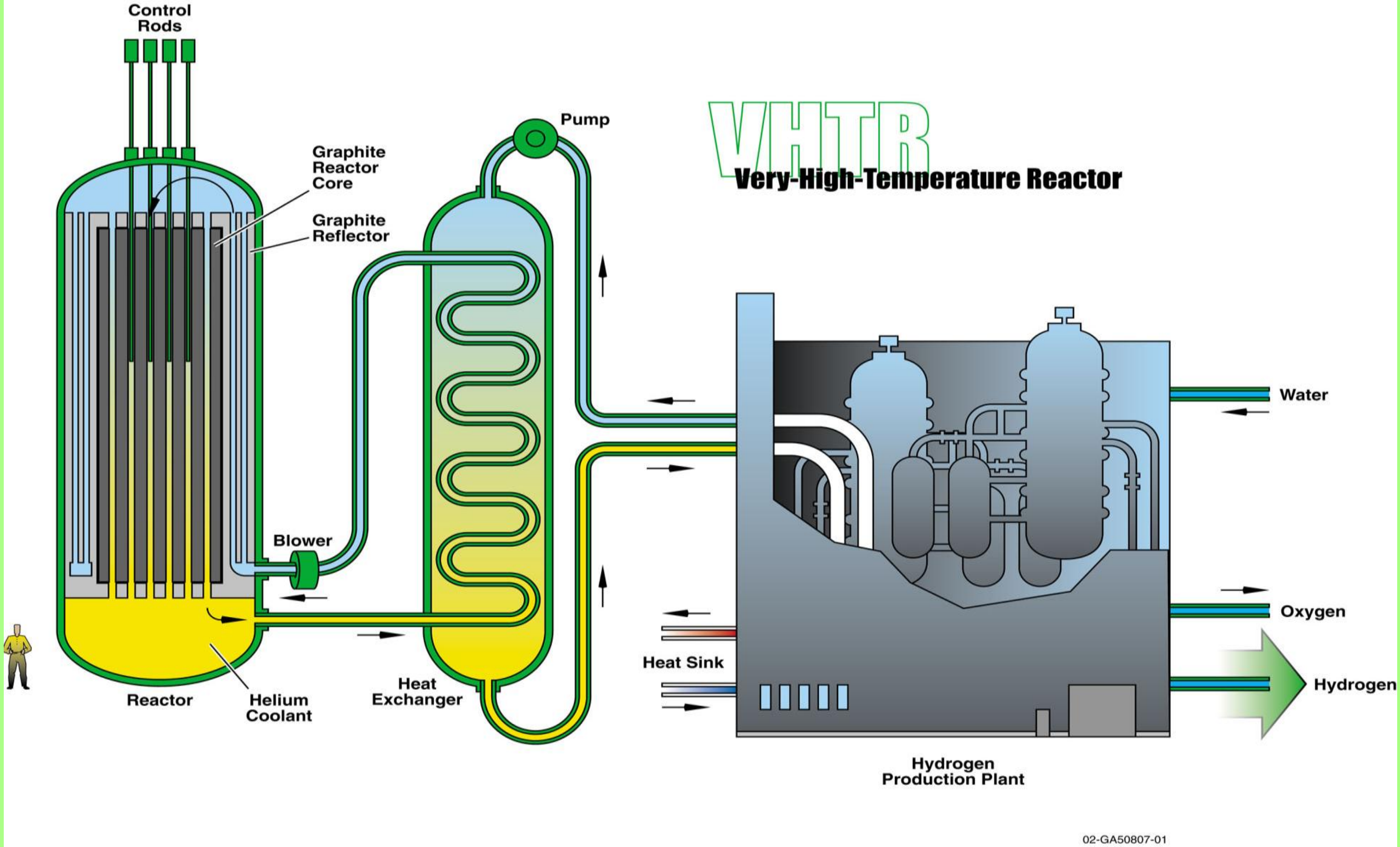
simplified systems

high efficiency

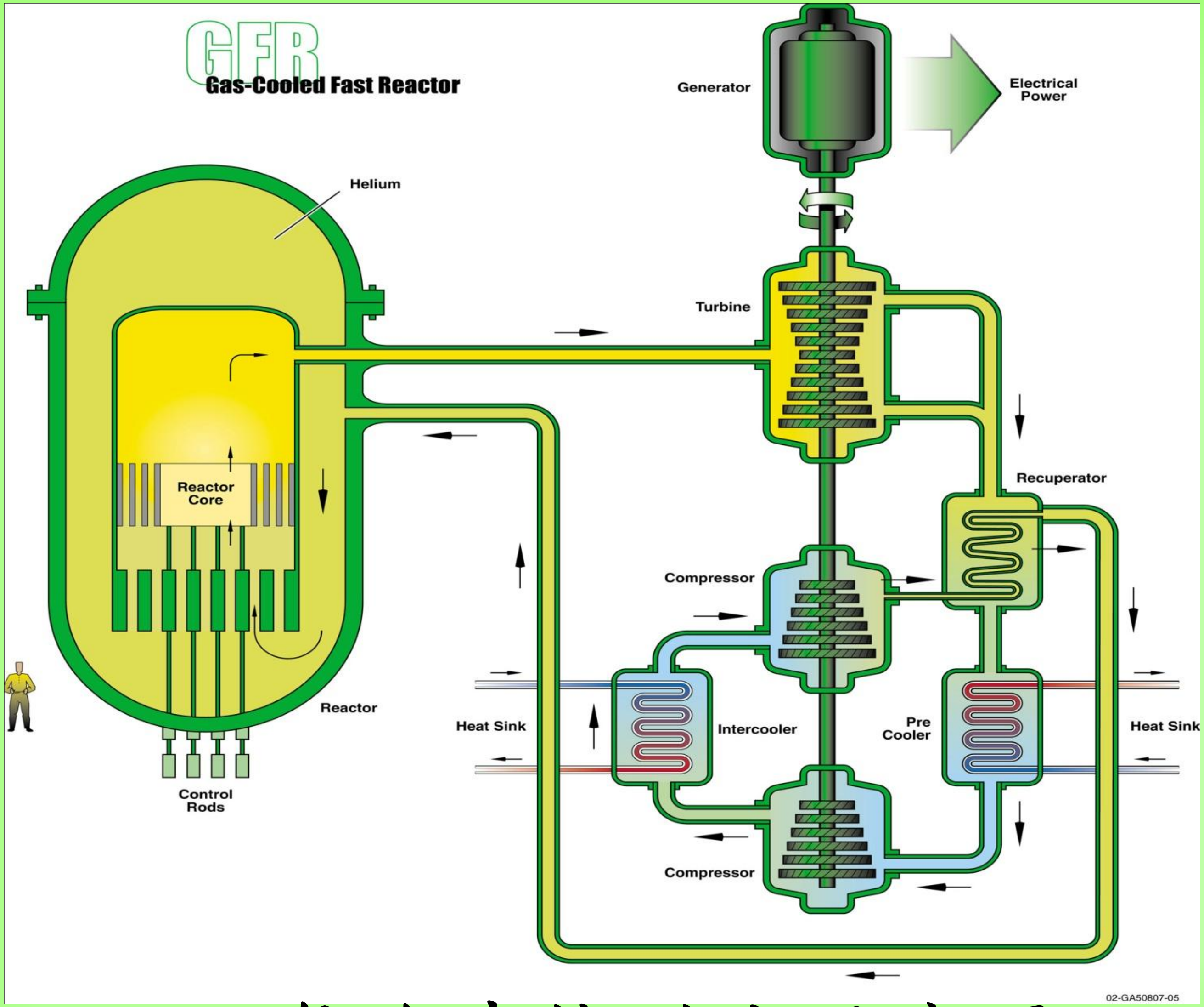
Sustainability

fuel utilization
waste toxicity

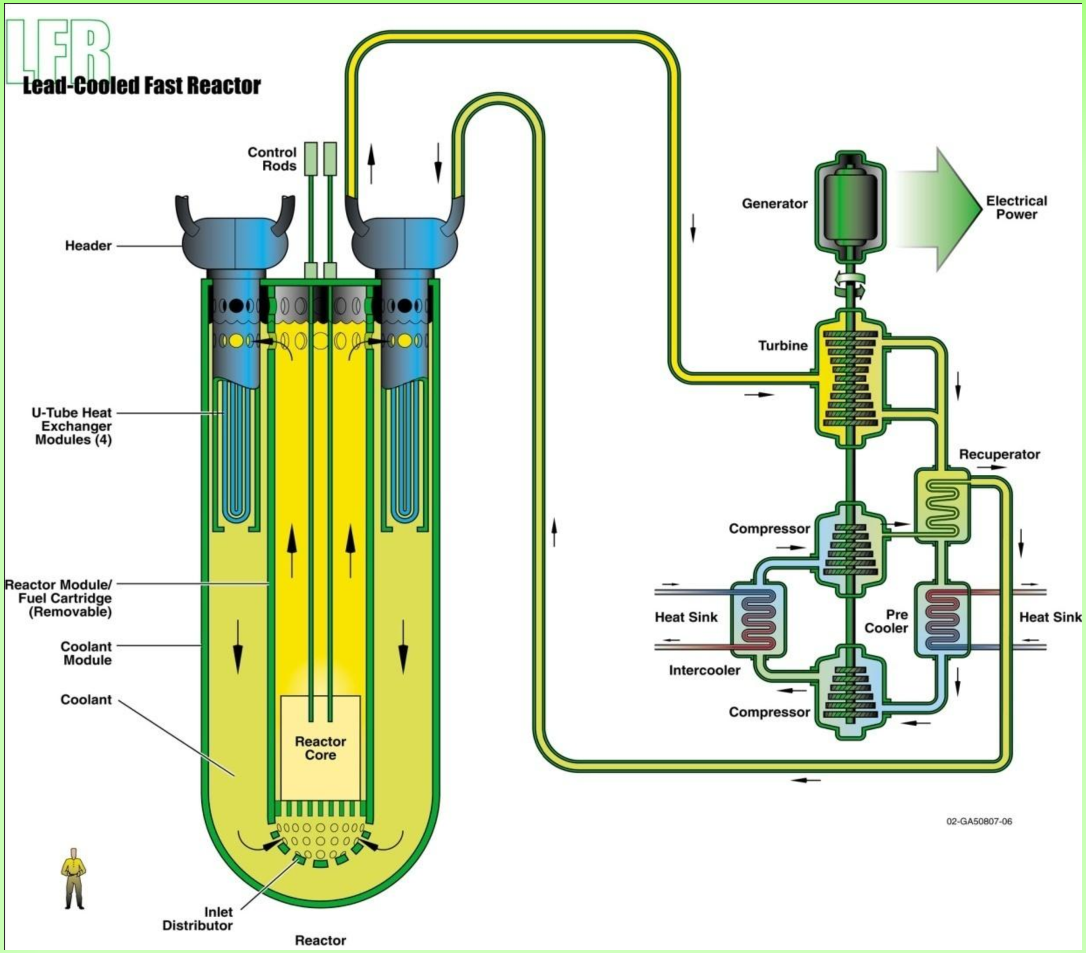
Non-Proliferation


Control Rods
Pump
VHTR
Very-High-Temperature Reactor
Graphite Reactor Core
Graphite Reflector
Blower
Water
Oxygen
Hydrogen
Heat Sink
Reactor
Helium Coolant
Heat Exchanger
Hydrogen Production Plant
02-GA50807-01

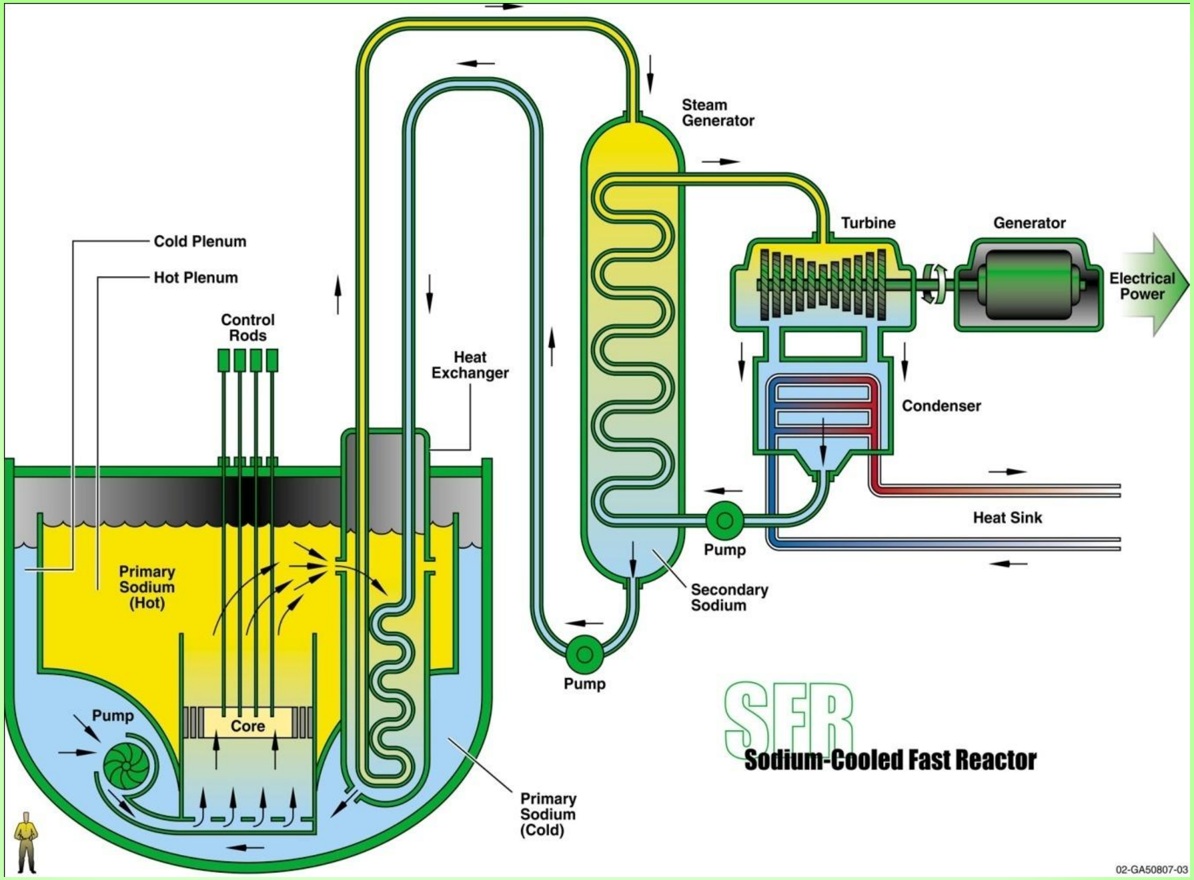
高溫氣冷反應器


GFR
Gas-Cooled Fast Reactor
Generator
Electrical Power
Helium
Turbine
Reactor Core
Recuperator
Compressor
Reactor
Heat Sink
Intercooler
Pre Cooler
Heat Sink
Control Rods
Compressor
02-GA50807-05

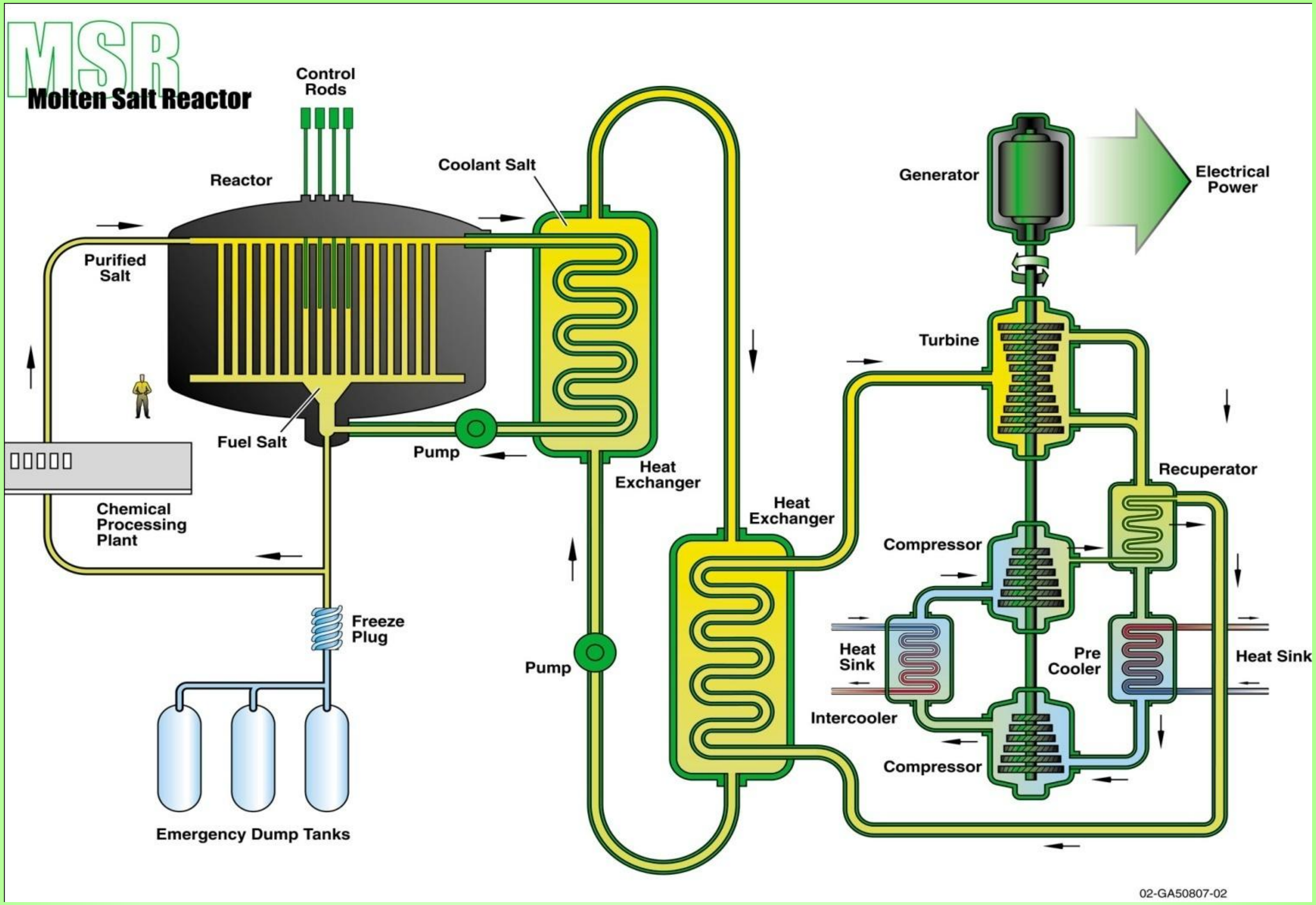
氣冷式快滋生反應器


LFR
Lead-Cooled Fast Reactor
Control Rods
Header
U-Tube Heat Exchanger Modules (4)
Reactor Module/ Fuel Cartridge (Removable)
Coolant Module
Coolant
Reactor Core
Inlet Distributor
Reactor
Generator
Electrical Power
Turbine
Recuperator
Compressor
Heat Sink
Pre Cooler
Heat Sink
Intercooler
Compressor
02-GA50807-06

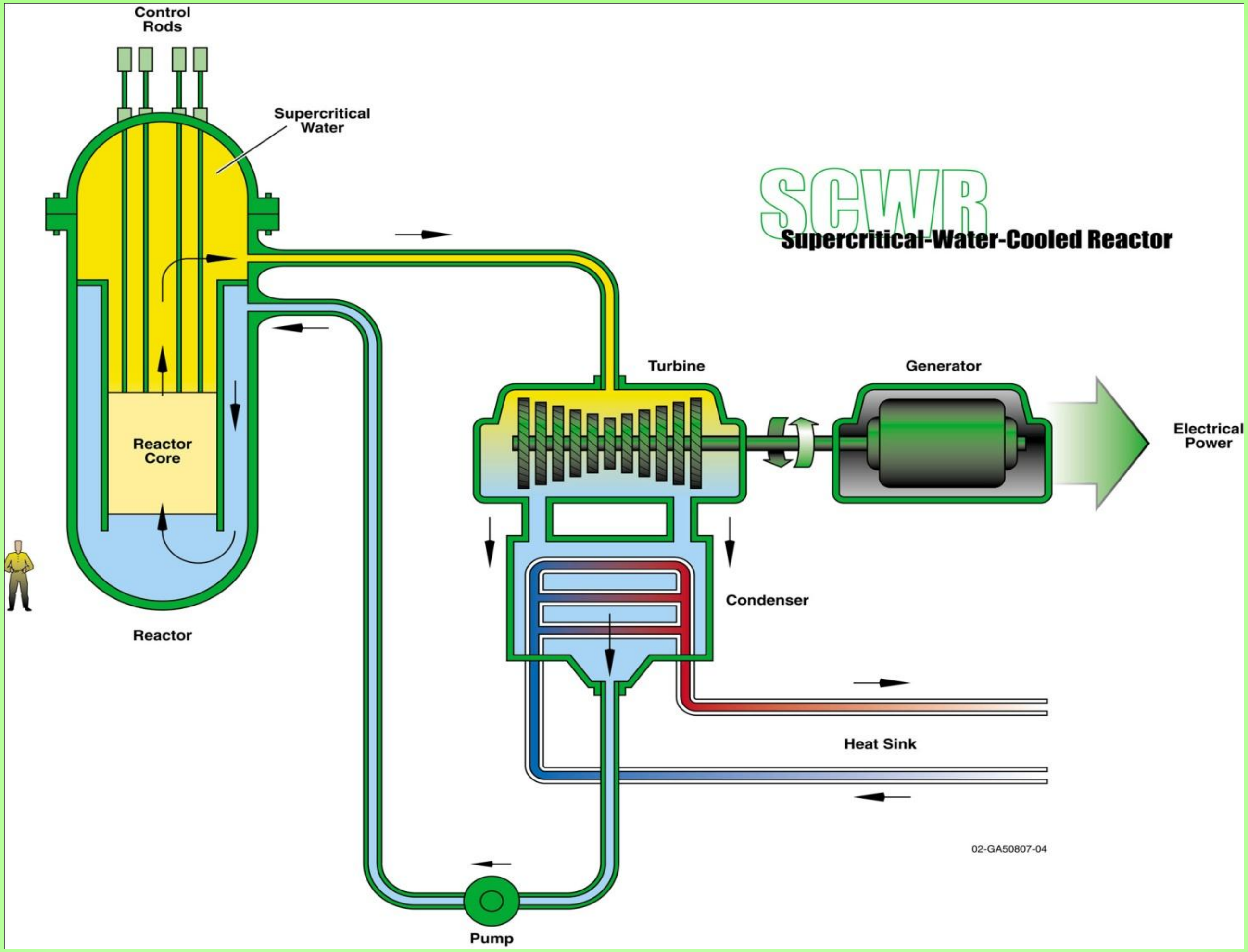
鉛冷式快滋生反應器


Steam Generator
Turbine
Generator
Electrical Power
Cold Plenum
Hot Plenum
Control Rods
Heat Exchanger
Condenser
Heat Sink
Pump
Secondary Sodium
Primary Sodium (Hot)
Pump
Pump
Core
Primary Sodium (Cold)
SFR
Sodium-Cooled Fast Reactor
02-GA50807-03

鈉冷式快滋生反應器


MSR
Molten Salt Reactor
Control Rods
Reactor
Coolant Salt
Purified Salt
Fuel Salt
Pump
Heat Exchanger
Chemical Processing Plant
Freeze Plug
Emergency Dump Tanks
Pump
Heat Exchanger
Generator
Electrical Power
Turbine
Recuperator
Compressor
Heat Sink
Pre Cooler
Heat Sink
Intercooler
Compressor
02-GA50807-02

熔鹽反應器


Control Rods
Supercritical Water
SCWR
Supercritical-Water-Cooled Reactor
Reactor Core
Reactor
Turbine
Generator
Electrical Power
Condenser
Heat Sink
02-GA50807-04
Pump

超臨界水冷反應器

Nuclear Rapidly Expanding In Asia

Japan: 55NPPs in operation (49GW) 30% of electricity 2NPPs under construction 11NPPs under planning (2017)

China: 10NPPs in operation(8GW), 5NPPs under construction, about 30 new NPPs will be completed (total 40 GW, 4% of electricity) and 18 under construction by 2020

India: 15NPPs in operation(3GW), 8NPPs under construction 20-40GW in 2015
500 MW FBR to be completed in 2010

In Asia(2)

ROK: 20NPPs in operation (17GW),(40% of Electricity) 4 NPPs under construction, 4 under planning

Viet Nam: The Prime Minister decided in Jan. 2006 2NPPs(2GW)in operation 2020

Indonesia: The President decided Jan in 2006 2NPPs (2GW) in operation 2018

Nuclear Renaissance in USA

USA:

103NPPs (127GW) in operation
No new construction after TMI Accident (1979)

Comprehensive Energy Act (2005)

Encouraging NPPs construction by tax exemption, insurance of financing

- Some 27 new NPPs under planning

Proposal of GNEP (Global Nuclear Energy Partnership) (2006) to develop and deploy technology for recycling SF not resulting in separated Pu.

Nuclear Renaissance in Europe (1)

France: 59NPPs(63GW) in operation
-EPR(1.6GW) to be in operation in 2020
-Commercial FBR in 2040

U K : 23NPPs (11GW) in operation
No new construction of NPP after 1989
-The Government announced in July, 2006 the new policy to start construction of NPPs for energy security

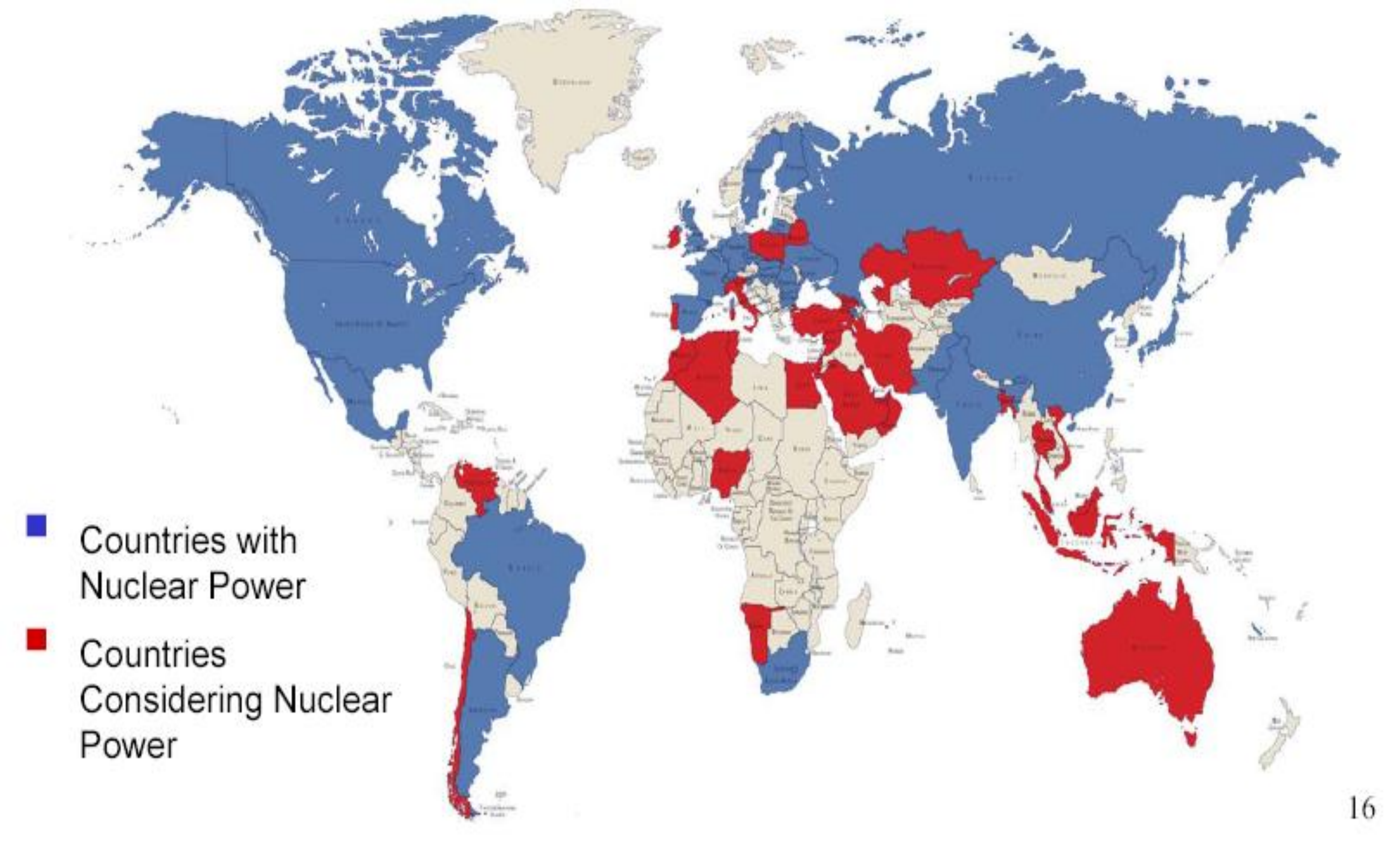
Russia: 31 NPPs (22GW) in operation, 4 NPPs under construction. Additional 57 NPPs to be in operation by 2030 (nuclear power share to be 25%)

Nuclear Renaissance in Europe (2)

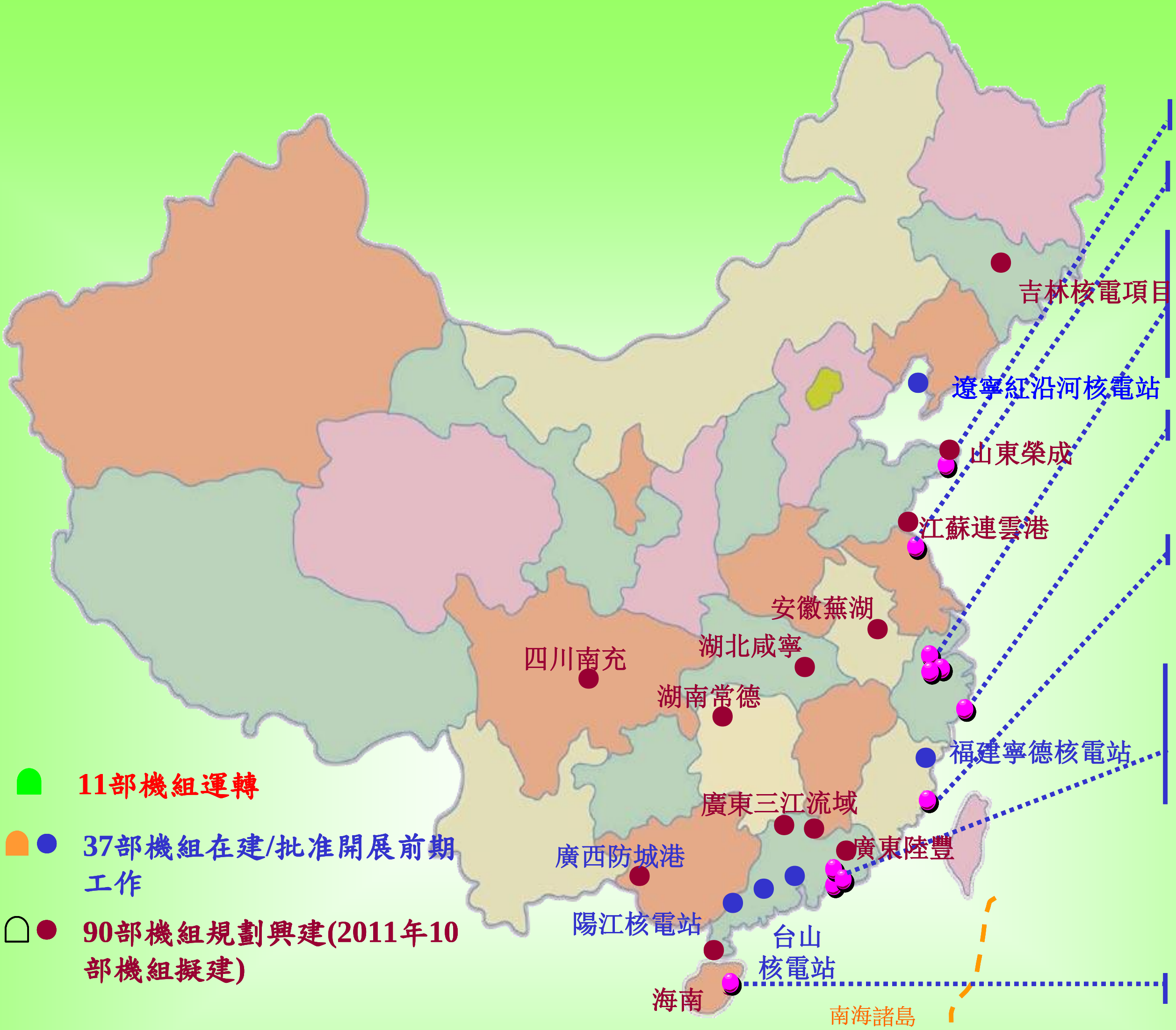
Finland: 4 NPPs (2.7GW) in operation
EPR (1.6GW) under construction to be in operation 2009

Poland: No NPP, 95% electricity by coals
New Administration announced the policy to start NPP construction to be operated in 2021-2022 (2006)

Turkey: Plan to built 5GW NPPs



From presentation of M. Dreicer of U.S. DoE at 4th Nuclear Energy NPT Workshop, Bunsun, Korea



海陽核電站	□ □
田灣核電站	🟩 🟩
秦山核電站	🟩 □ □
秦山第二核電站	🟩 🟩 🟧 🟧
秦山第三核電站	🟩 🟩
三門核電站	□ □
福清核電站	□ □
大亞灣核電站	🟩 🟩
嶺澳核電站	🟩 🟩
嶺東核電站	🟧 🟧
海南昌江核電站	□ □

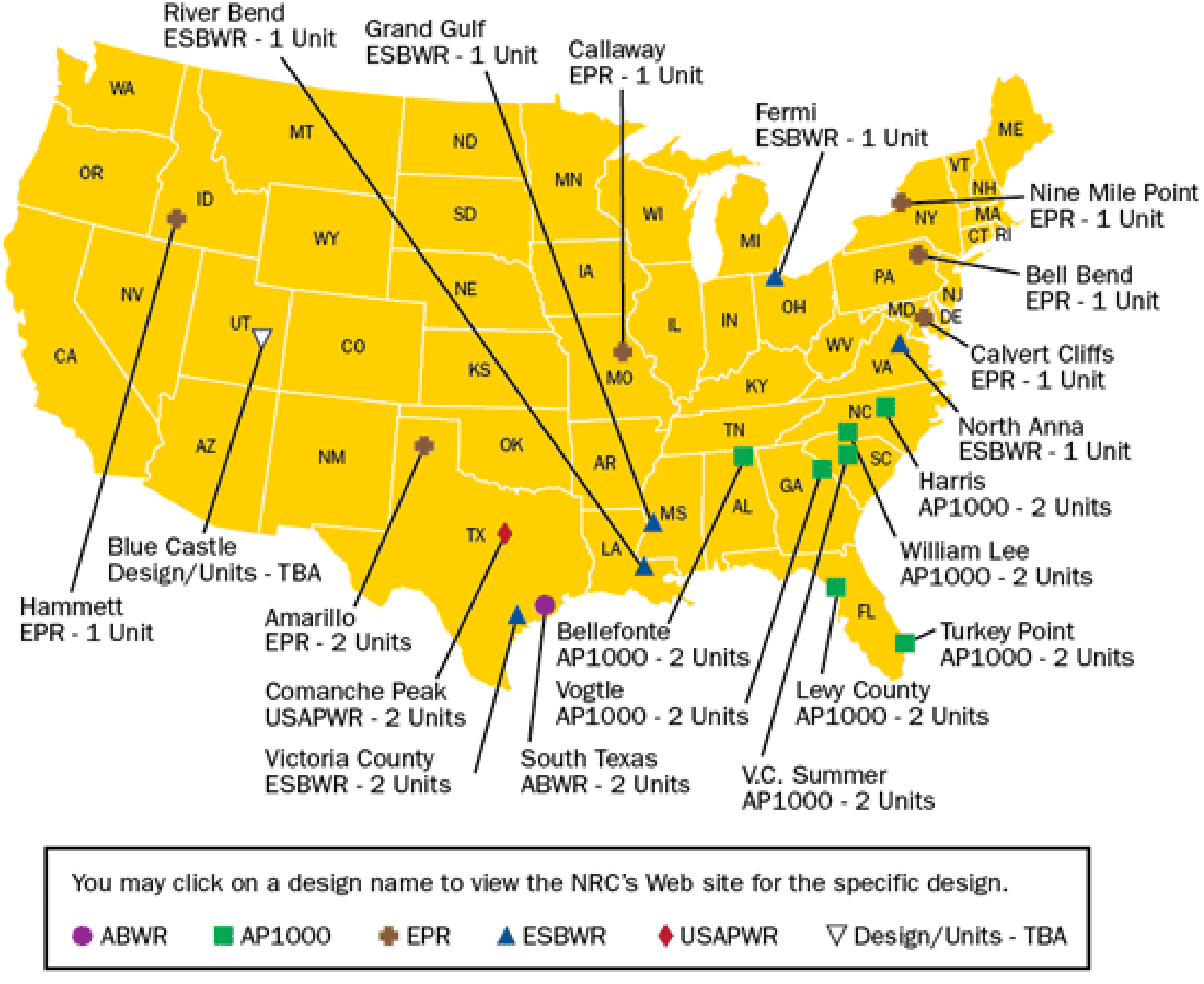
🟩 **11部機組運轉**

🟧 🔵 **37部機組在建/批准開展前期工作**

□ 🔴 **90部機組規劃興建(2011年10部機組擬建)**

中國大陸核電廠分佈圖

美國新申請核電機組型式與位置



You may click on a design name to view the NRC's Web site for the specific design.

● ABWR　🟩 AP1000　✚ EPR　▲ ESBWR　♦ USAPWR　▽ Design/Units - TBA

投