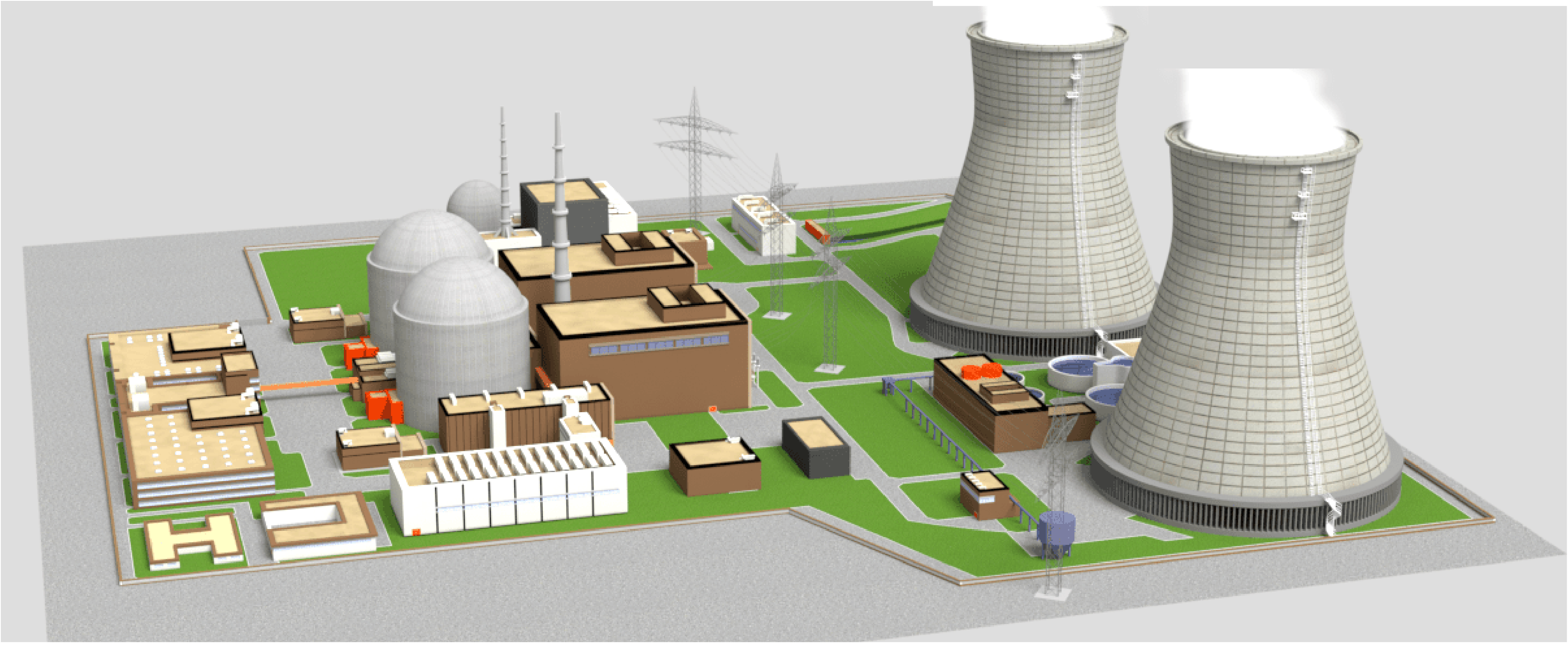
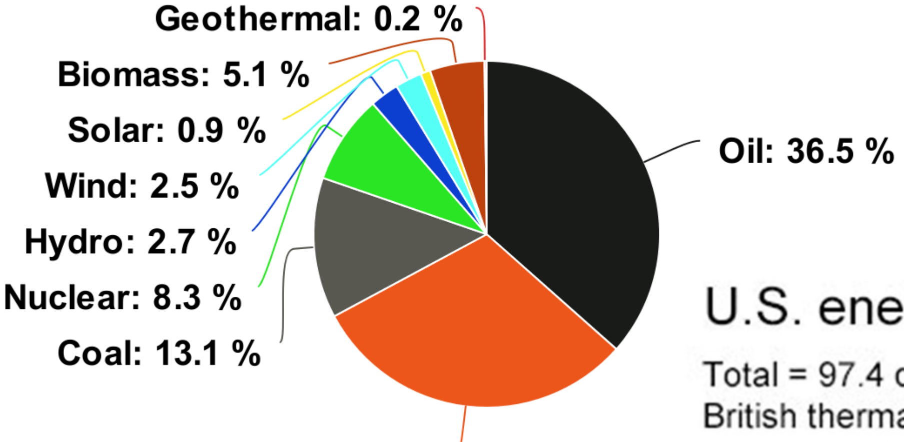
Nuclear power plant



U.S. Energy Consumption 2018

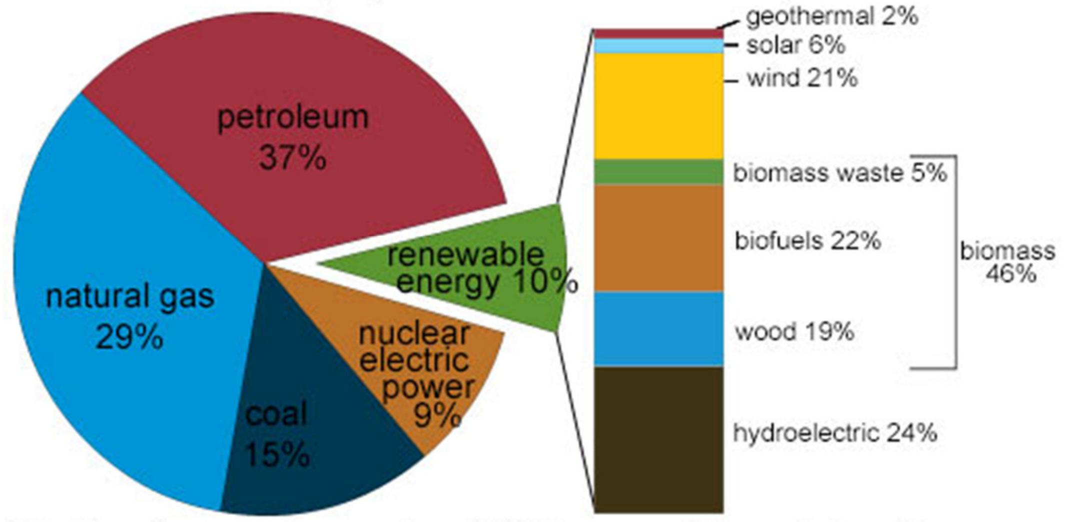
(Percentage)



U.S. energy consumption by energy source, 2016

Total = 97.4 quadrillion British thermal units (Btu)

Total = 10.2 quadrillion Btu

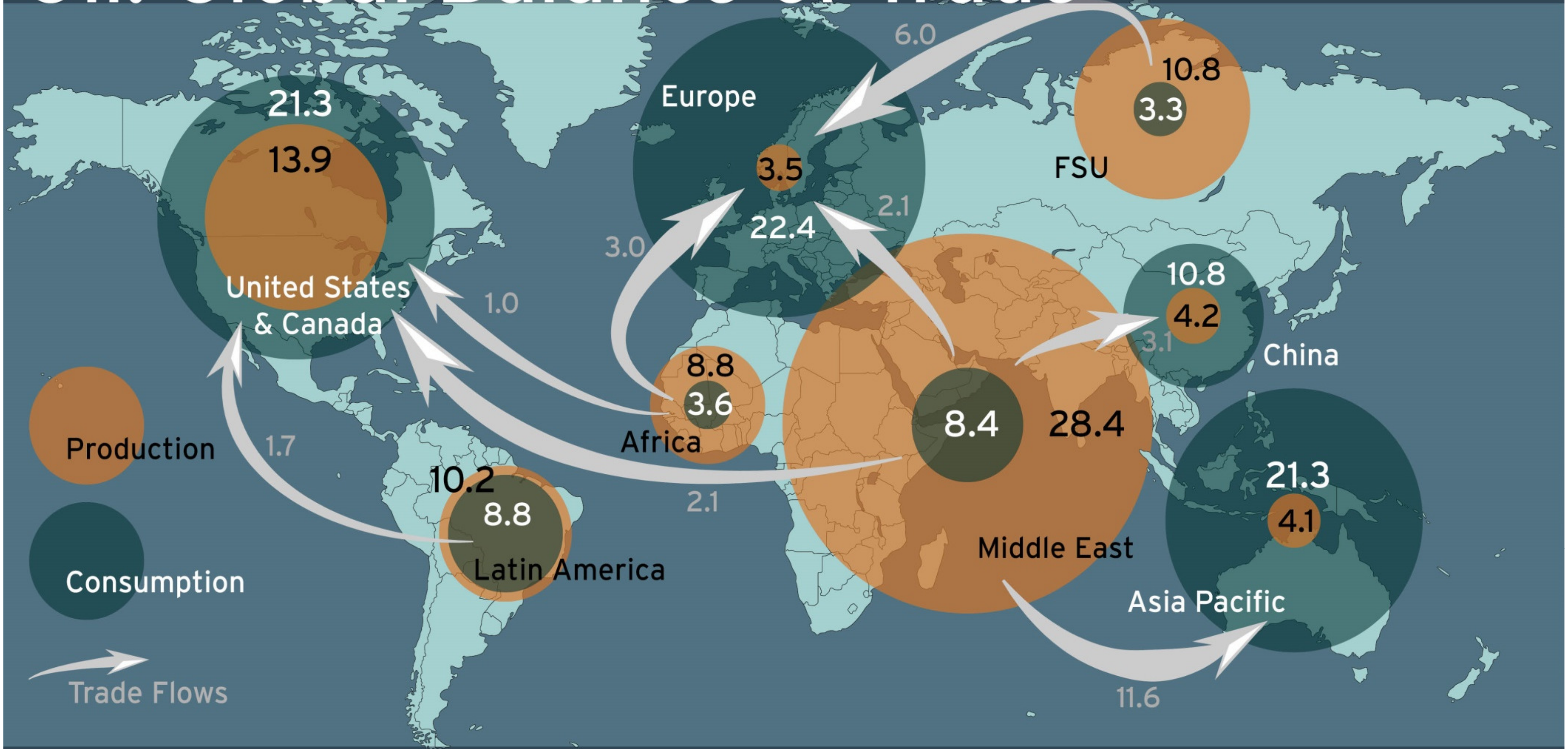


Note: Sum of components may not equal 100% because of independent rounding.

Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2017, preliminary data

eia

Oil: Global Balance of Trade

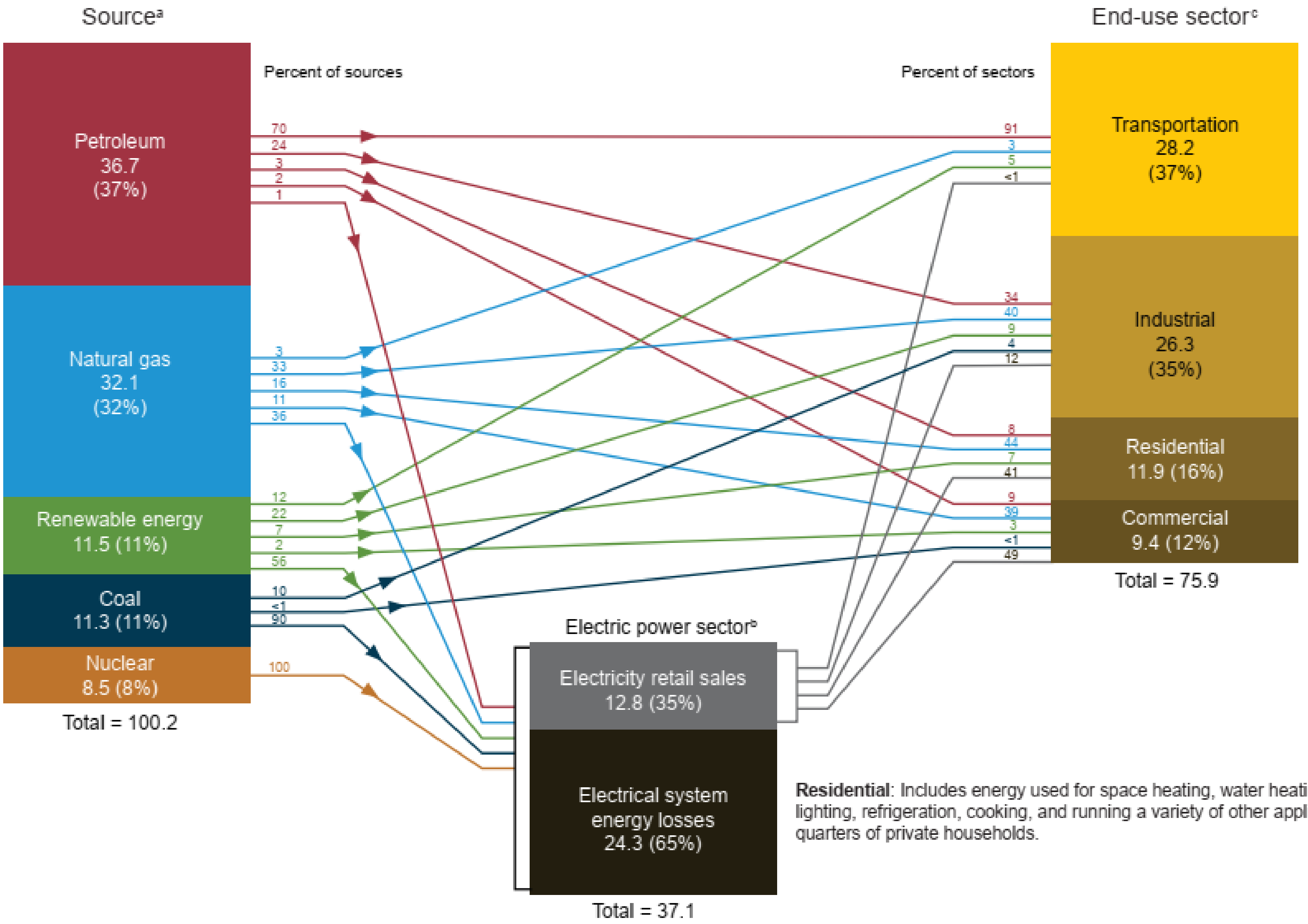


Source: SAFE analysis based on data from BP Statistical Review, all values in million barrels per day
Production and consumption values represented at scale. Only trade flows above 1 mbd represented

Securing America's Future Energy

U.S. energy consumption by source and sector, 2019

(Quadrillion Btu)



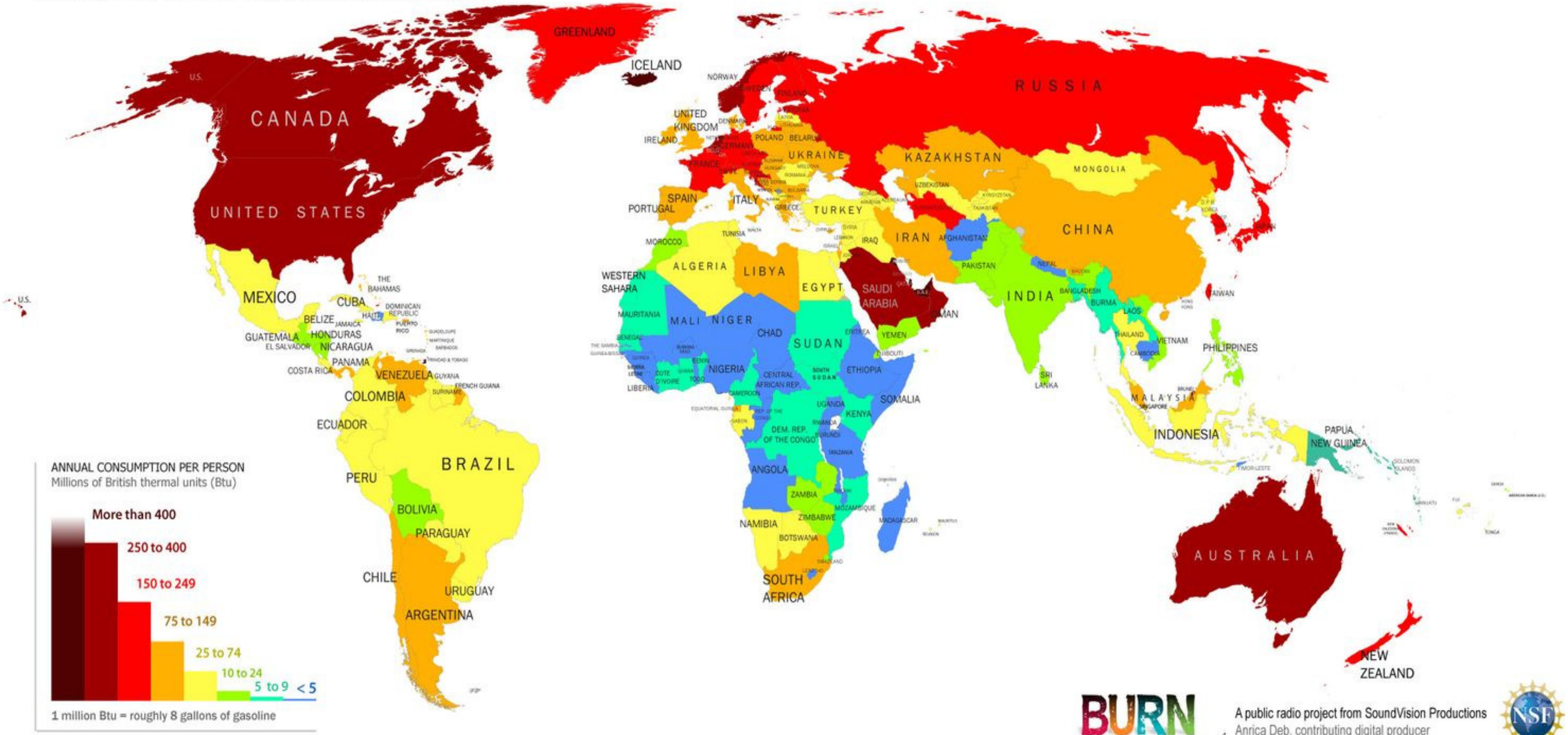
Residential: Includes energy used for space heating, water heating, air conditioning lighting, refrigeration, cooking, and running a variety of other appliances in the living quarters of private households.

Electricity retail sales: The amount of electricity sold to customers purchasing electricity for their own use and not for resale.

Commercial: Includes energy consumed by businesses; federal, state, and local governments; other private and public organizations, such as religious, social, or fraternal groups; institutional living quarters; sewage treatment facilities; and generators that produce electricity and/or useful thermal output primarily to support the activities of the above-mentioned commercial establishments.

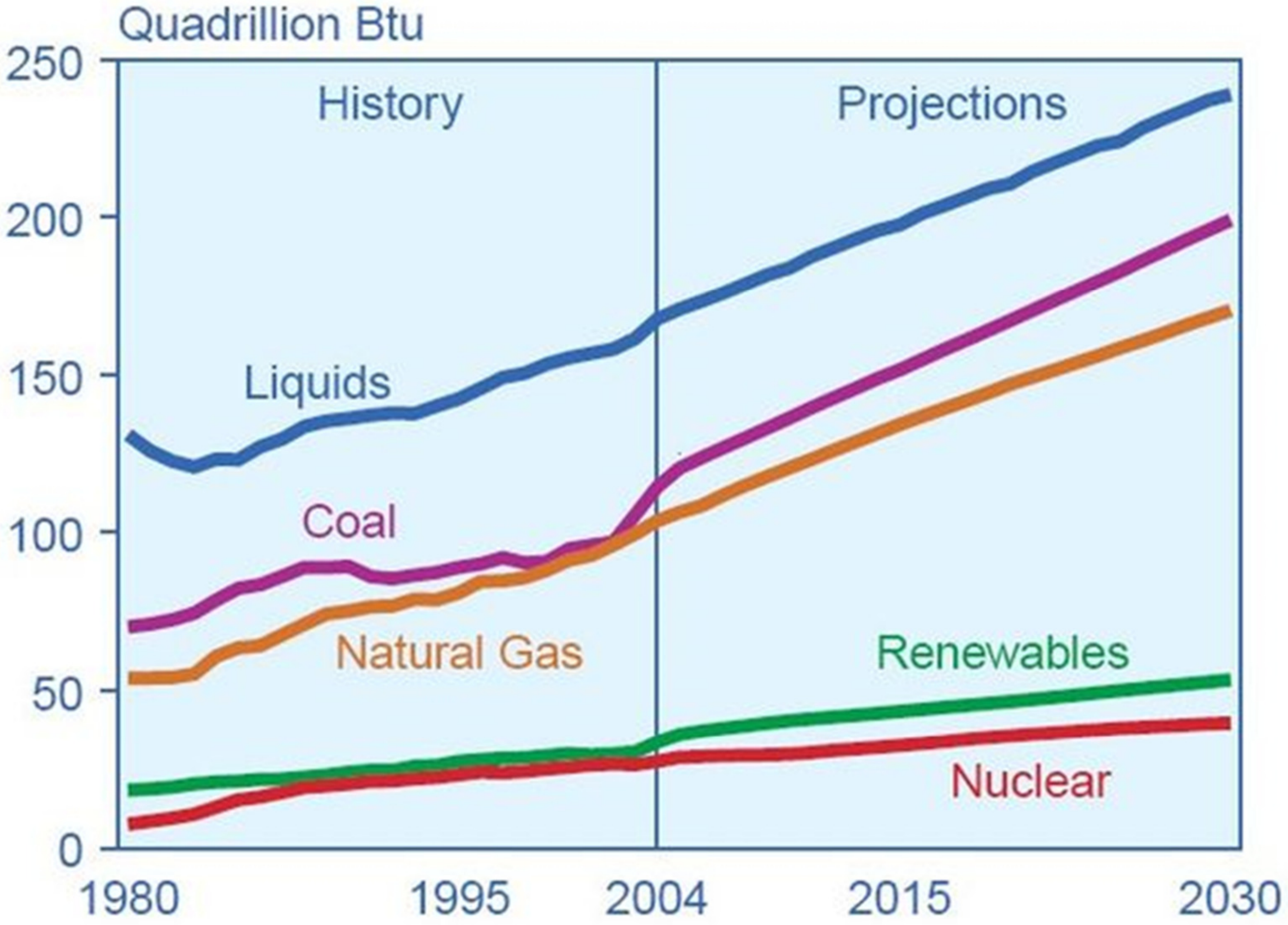
Energy Consumption Per Person, by country, 2010.

SOURCES: U.S.Energy Information Administration, International Energy Agency, CIA World Factbook, U.N. Dep't of Economics and Social Affairs

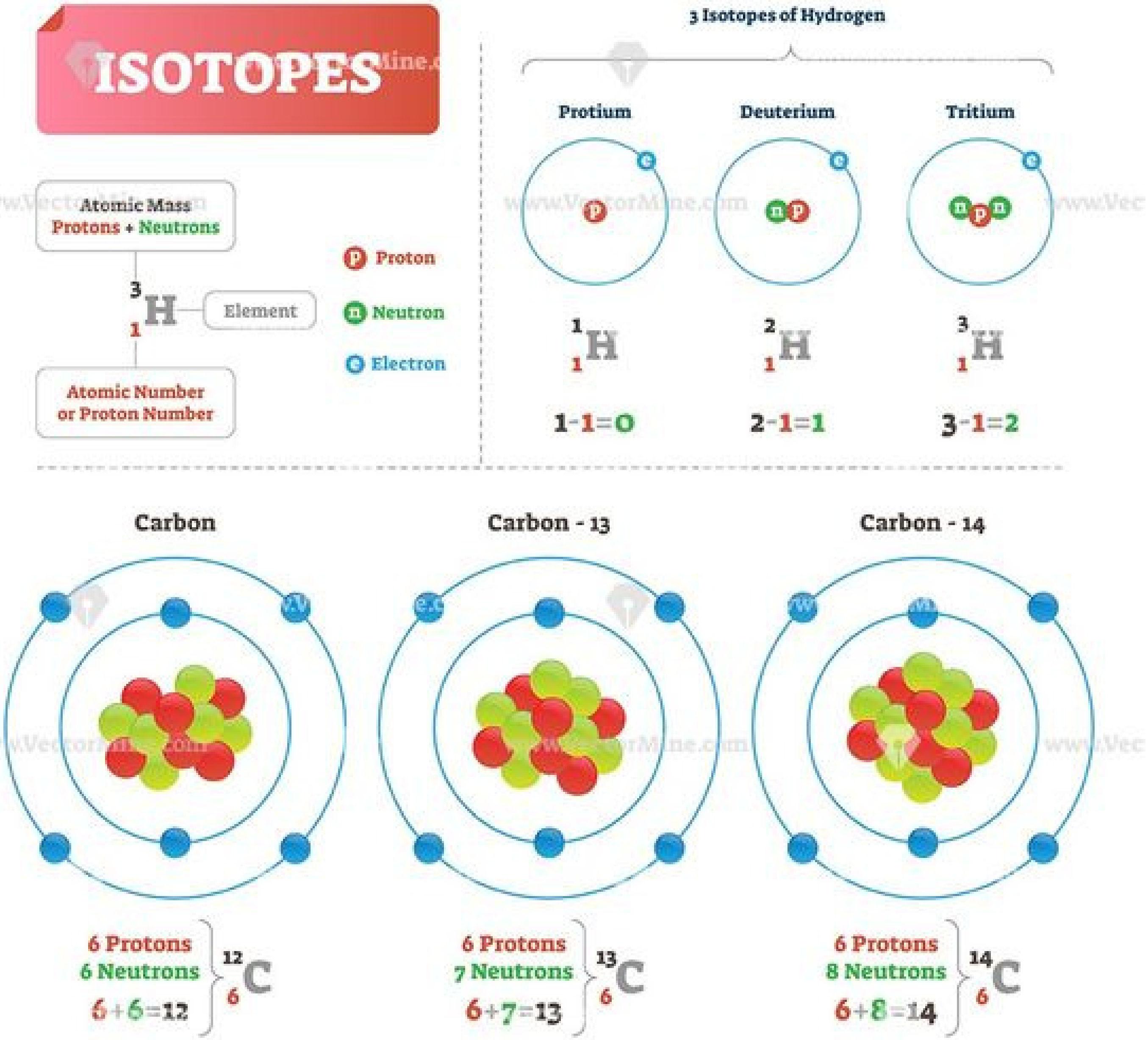


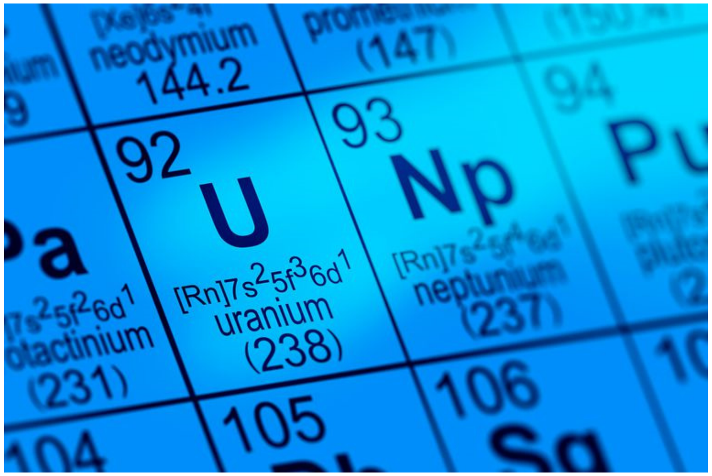
BURN
an energy journal
A public radio project from SoundVision Productions
Anrica Deb, contributing digital producer

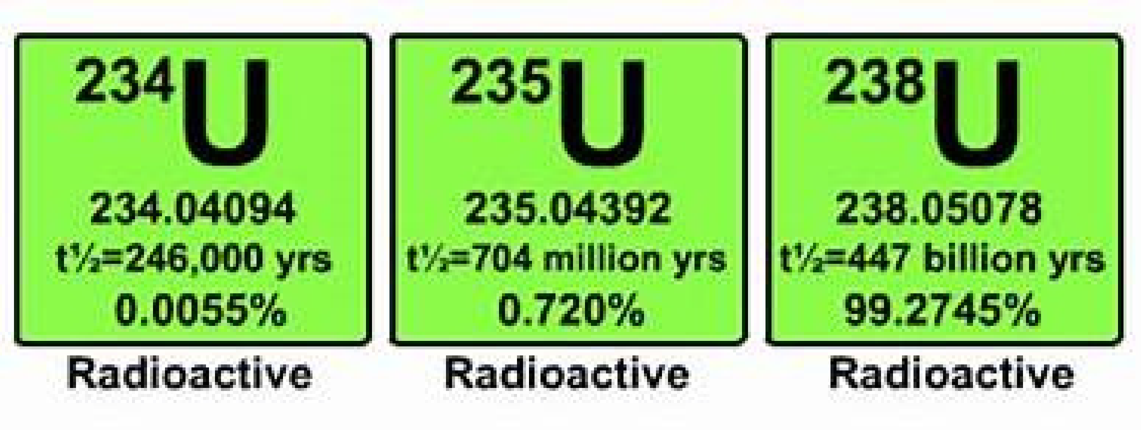
Figure 4. World Marketed Energy Use by Fuel Type, 1980-2030



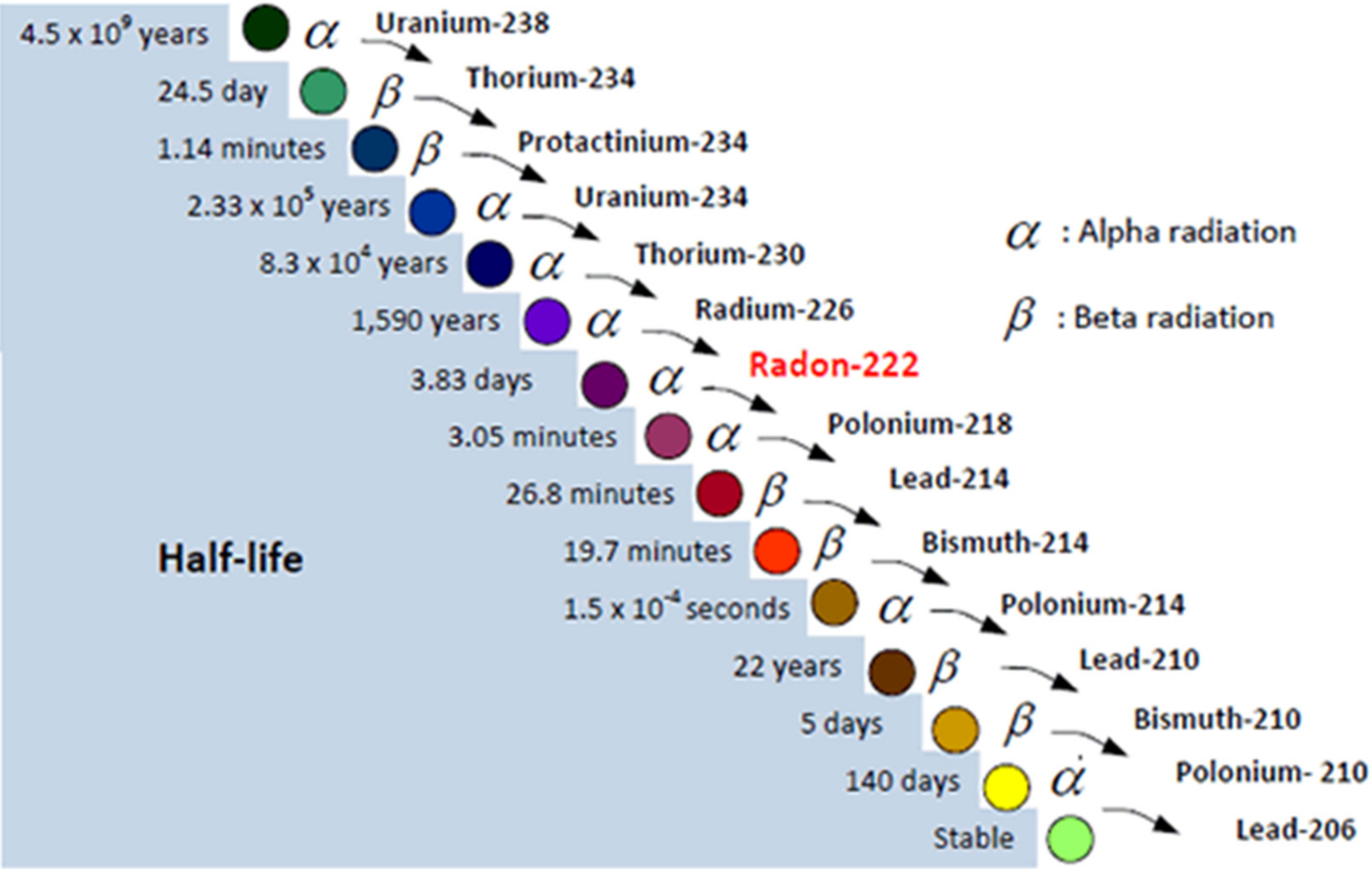
Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets (2007).


ISOTOPES
Atomic Mass
Protons + Neutrons
$^{3}_{1}H$
Element
Atomic Number
or Proton Number
p Proton
n Neutron
e Electron
3 Isotopes of Hydrogen
Protium
Deuterium
Tritium
e
p
n p
n p n
$^{1}_{1}H$
$^{2}_{1}H$
$^{3}_{1}H$
1-1=0
2-1=1
3-1=2
Carbon
Carbon - 13
Carbon - 14
6 Protons
6 Neutrons
6+6=12
$^{12}_{6}C$
6 Protons
7 Neutrons
6+7=13
$^{13}_{6}C$
6 Protons
8 Neutrons
6+8=14
$^{14}_{6}C$





^{234}U	^{235}U	^{238}U
234.04094	235.04392	238.05078
t½=246,000 yrs	t½=704 million yrs	t½=447 billion yrs
0.0055%	0.720%	99.2745%
Radioactive	Radioactive	Radioactive



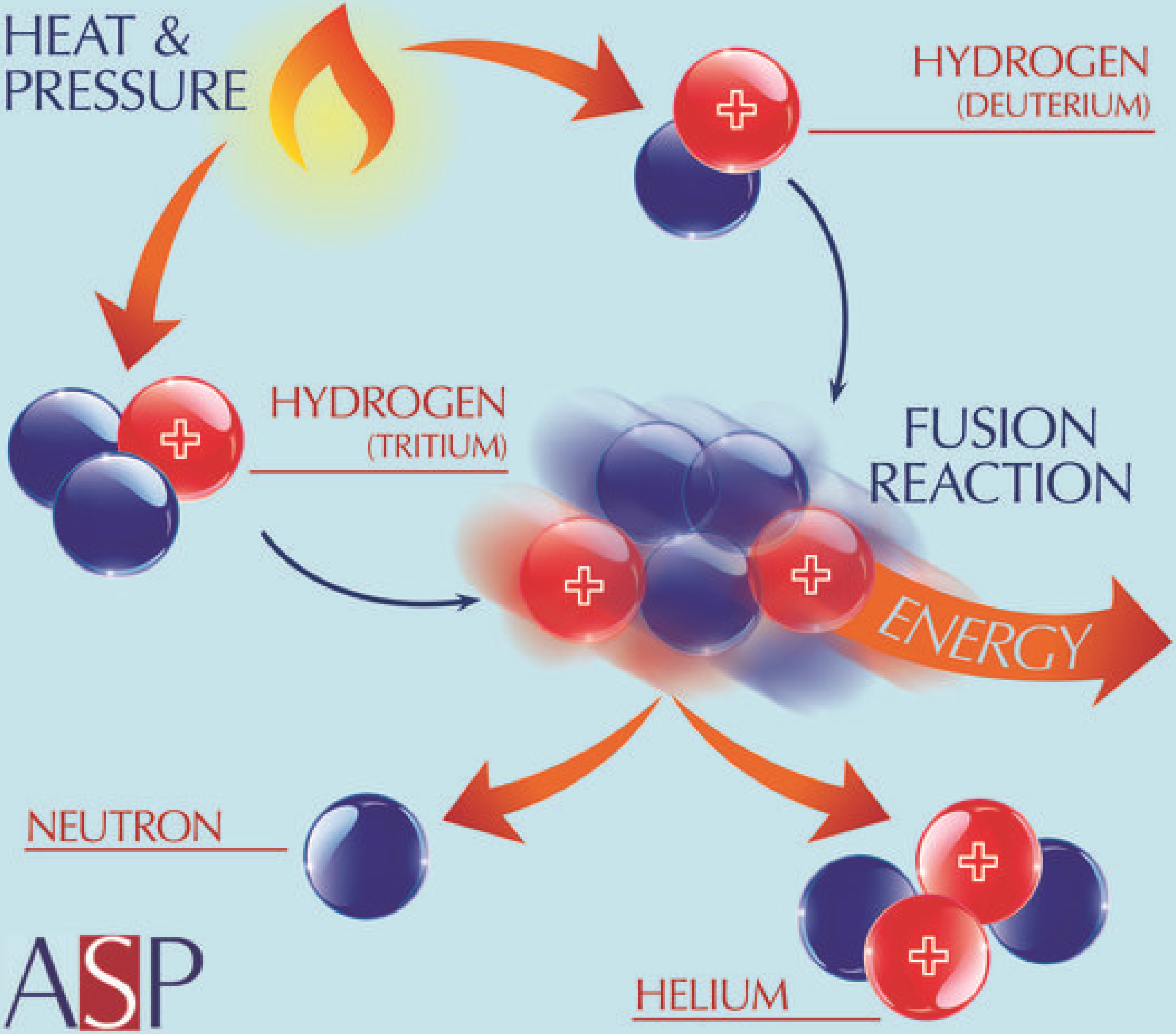
Half-life

4.5×10^9 years	α	Uranium-238
24.5 day	β	Thorium-234
1.14 minutes	β	Protactinium-234
2.33×10^5 years	α	Uranium-234
8.3×10^4 years	α	Thorium-230
1,590 years	α	Radium-226
3.83 days	α	Radon-222
3.05 minutes	α	Polonium-218
26.8 minutes	β	Lead-214
19.7 minutes	β	Bismuth-214
1.5×10^{-4} seconds	α	Polonium-214
22 years	β	Lead-210
5 days	β	Bismuth-210
140 days	α	Polonium- 210
Stable		Lead-206

α : Alpha radiation

β : Beta radiation

WHAT IS FUSION?



HEAT &
PRESSURE

HYDROGEN
(DEUTERIUM)

HYDROGEN
(TRITIUM)

FUSION
REACTION

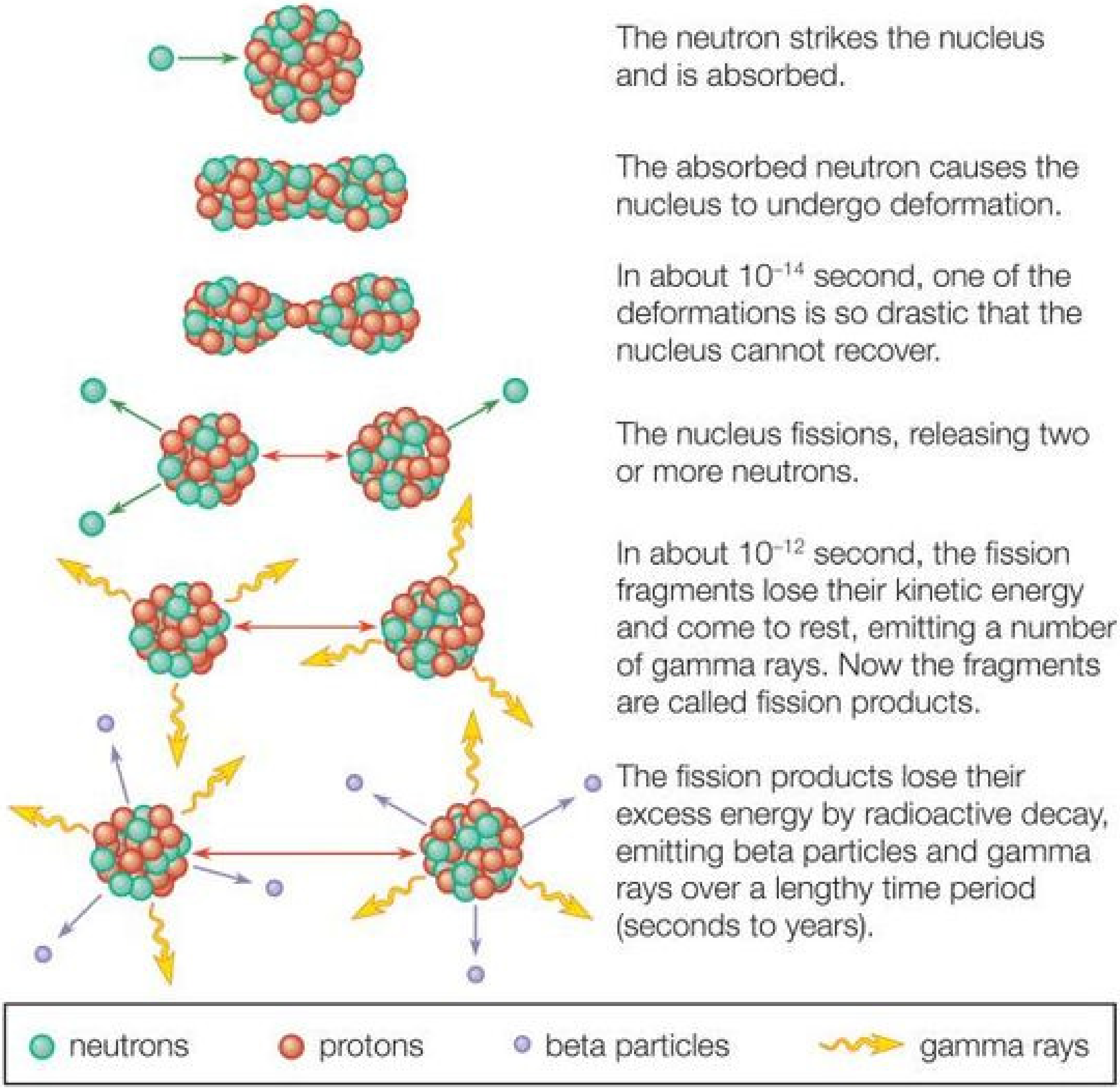
ENERGY

NEUTRON

HELIUM

ASP
American Security Project

Nuclear Fission



The neutron strikes the nucleus and is absorbed.

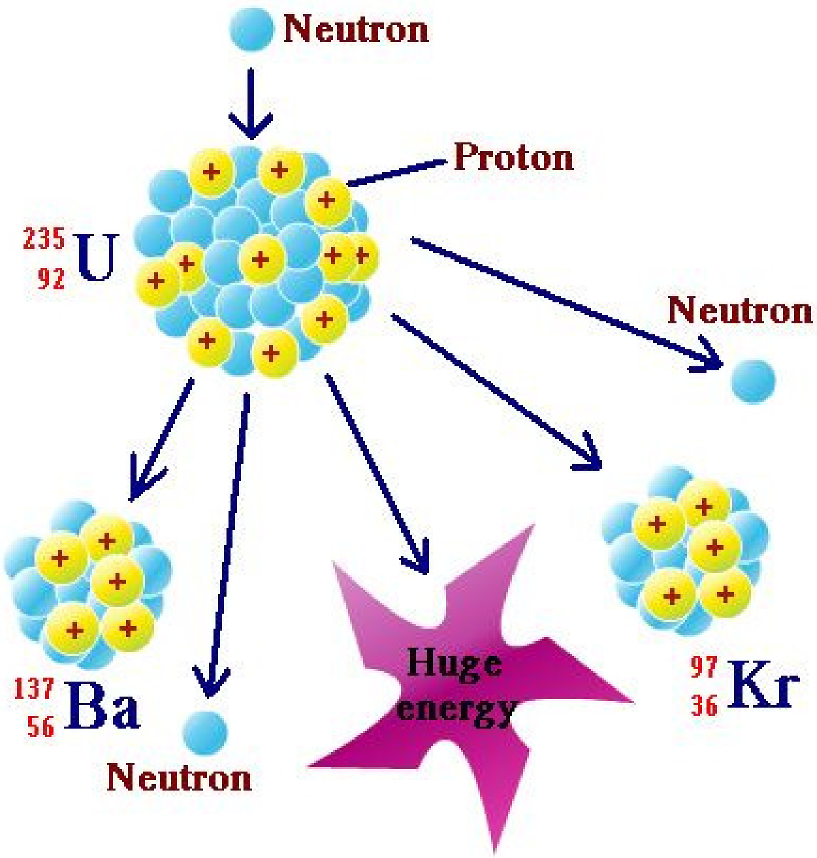
The absorbed neutron causes the nucleus to undergo deformation.

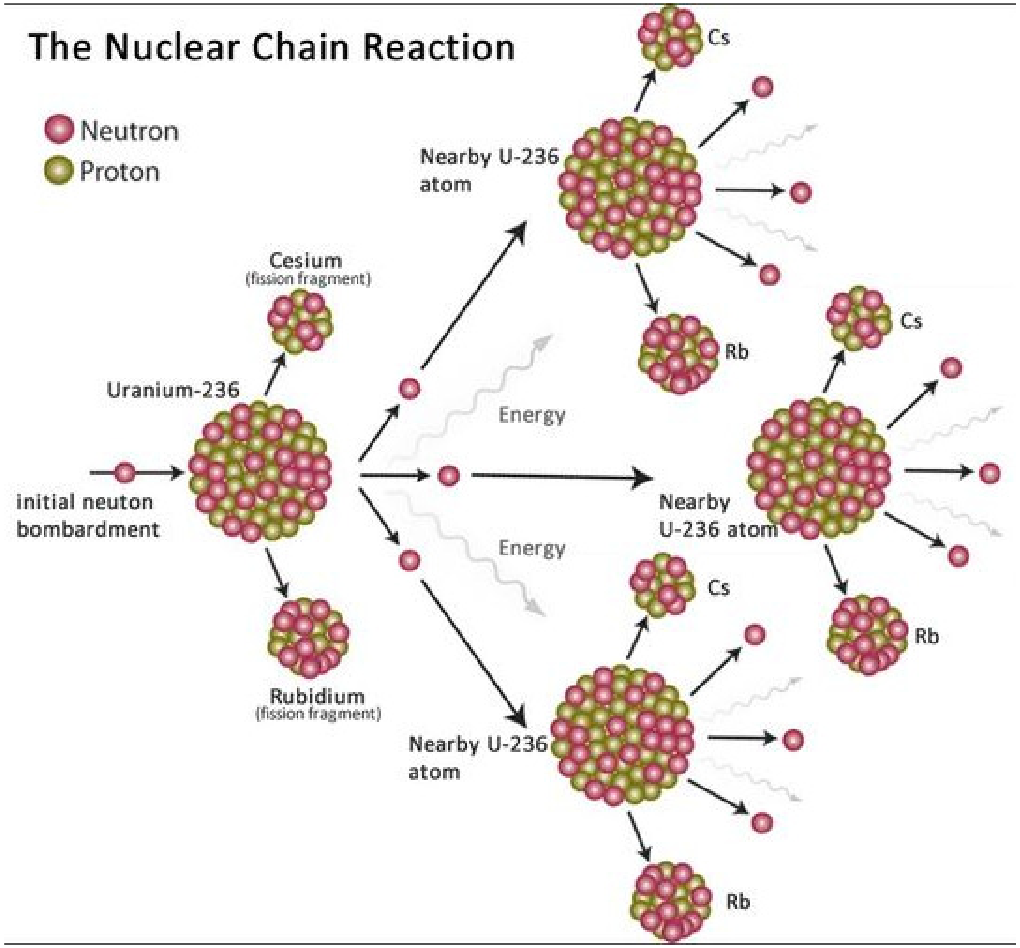
In about 10^{-14} second, one of the deformations is so drastic that the nucleus cannot recover.

The nucleus fissions, releasing two or more neutrons.

In about 10^{-12} second, the fission fragments lose their kinetic energy and come to rest, emitting a number of gamma rays. Now the fragments are called fission products.

The fission products lose their excess energy by radioactive decay, emitting beta particles and gamma rays over a lengthy time period (seconds to years).


Neutron
Proton
$^{235}_{92}$U
Neutron
Huge energy
$^{137}_{56}$Ba
Neutron
$^{97}_{36}$Kr

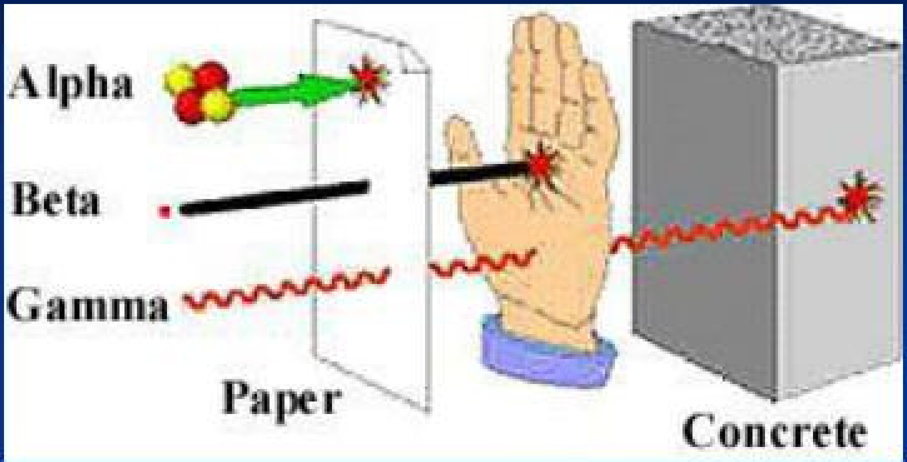

The Nuclear Chain Reaction
Neutron
Proton
Cs
Nearby U-236 atom
Cesium (fission fragment)
Rb
Cs
Uranium-236
Energy
initial neuton bombardment
Nearby U-236 atom
Energy
Cs
Rb
Rubidium (fission fragment)
Nearby U-236 atom
Rb

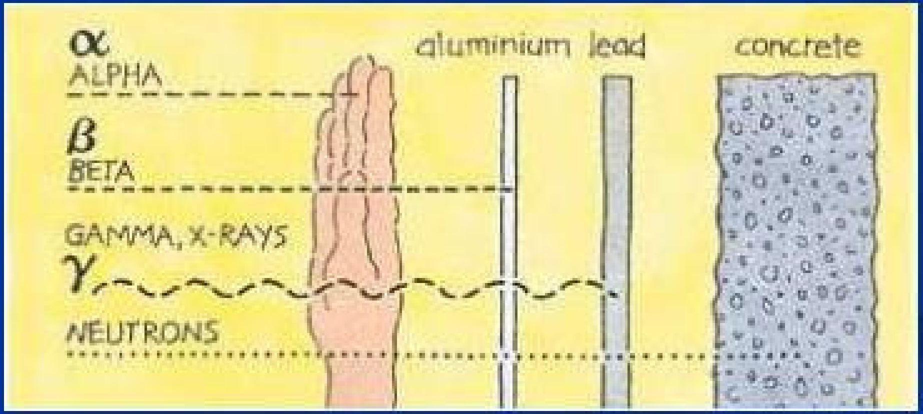
Definitions

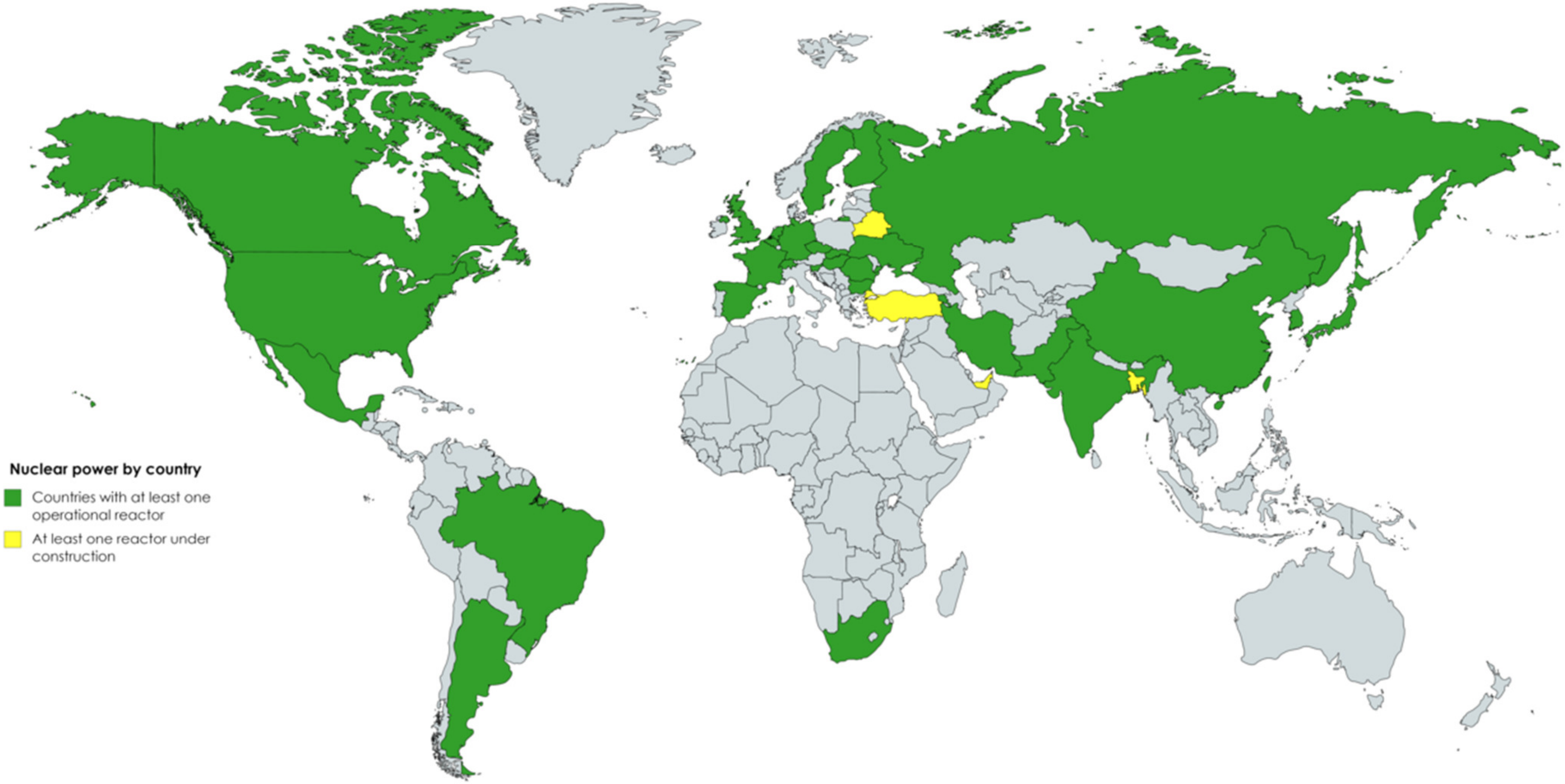
- **Radiation:**

  particles: neutrons, alpha particles, and beta particles

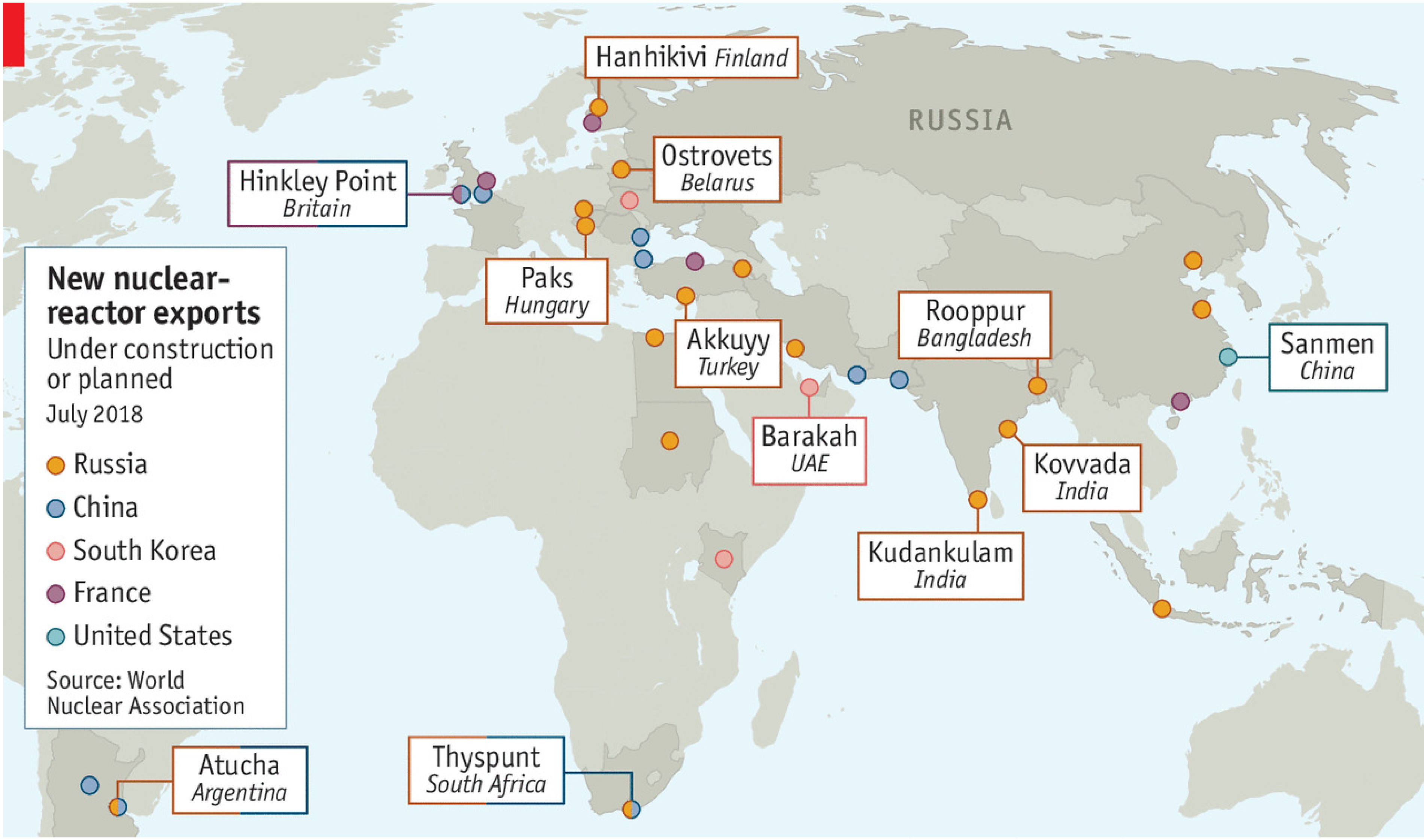
  energy : waves of pure energy, such as gamma and X-rays.







Created with mapchart.net ©



New nuclear-reactor exports

Under construction or planned

July 2018

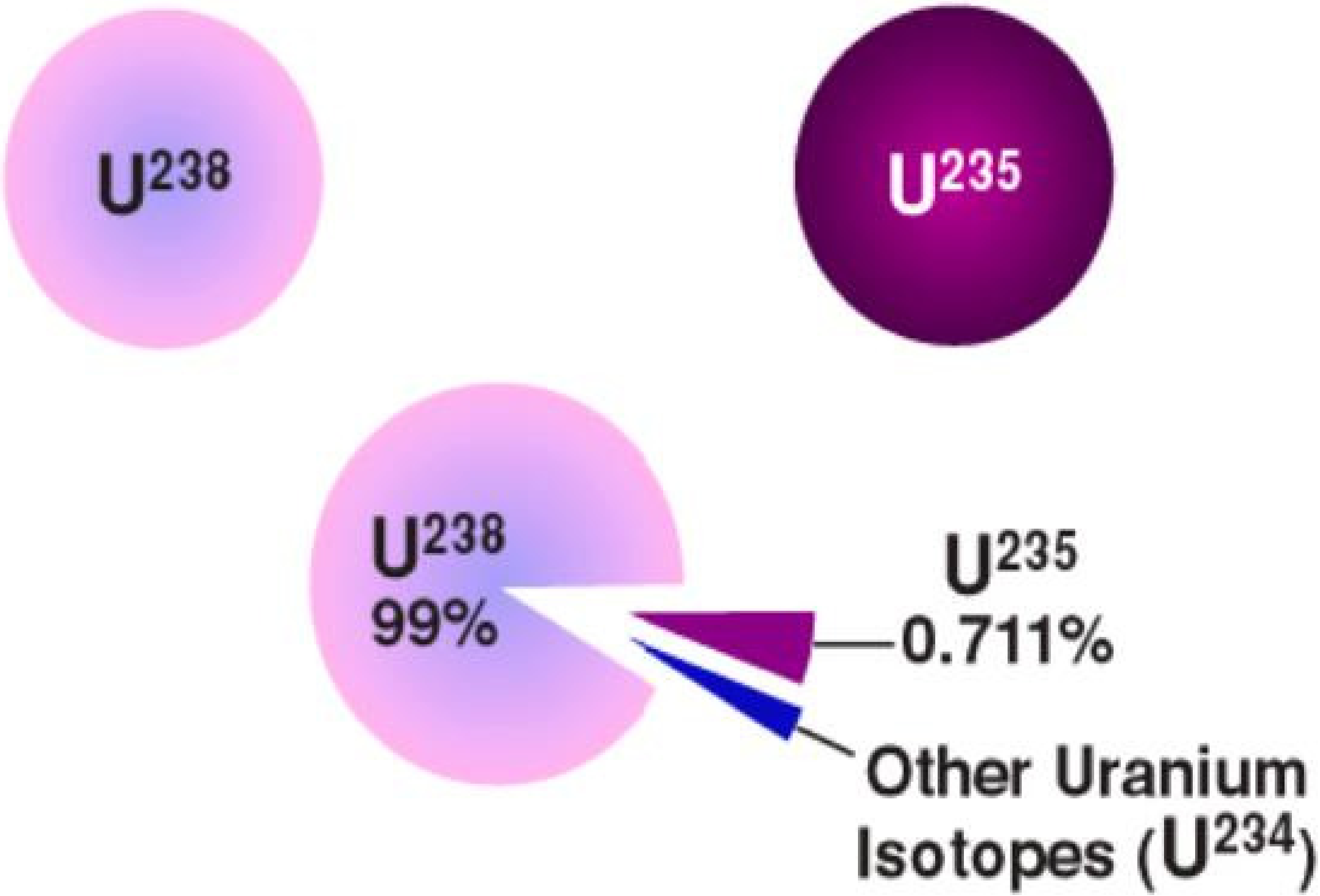
- ● Russia
- ● China
- ● South Korea
- ● France
- ● United States

Source: World Nuclear Association

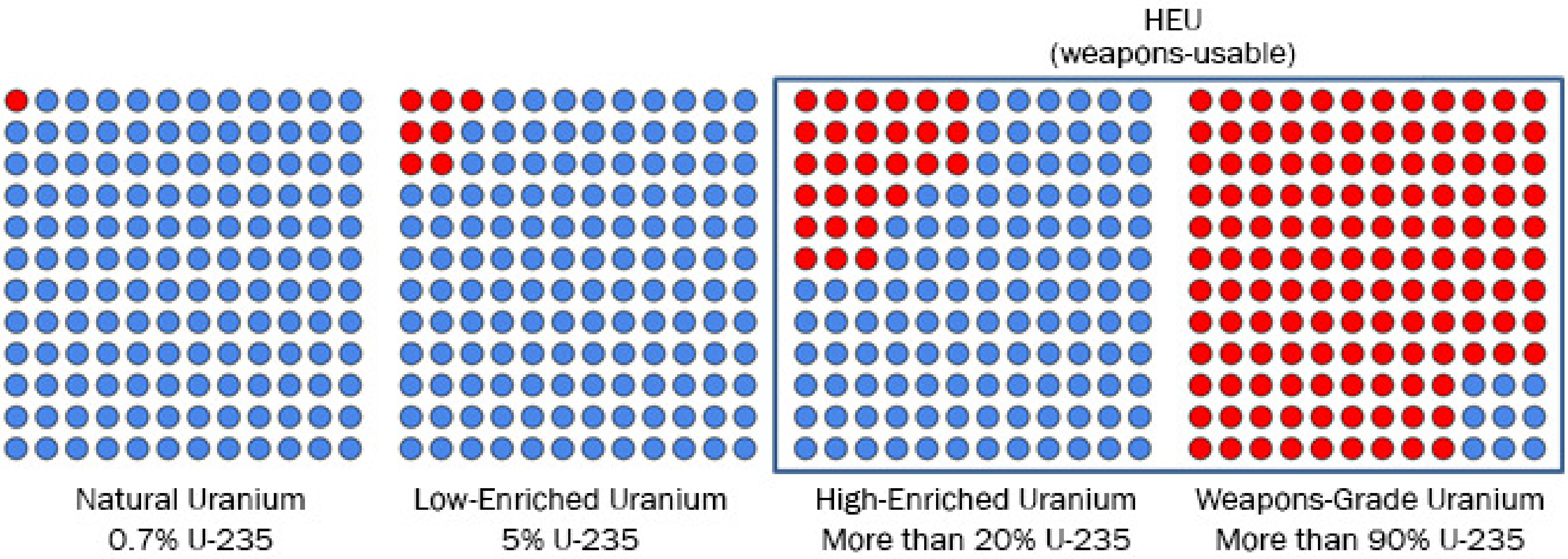
The Economist

All Uranium Is Not Created Equal!

A sample of any given element usually contains different kinds of atoms of that element. These atoms have different masses. These are called isotopes.

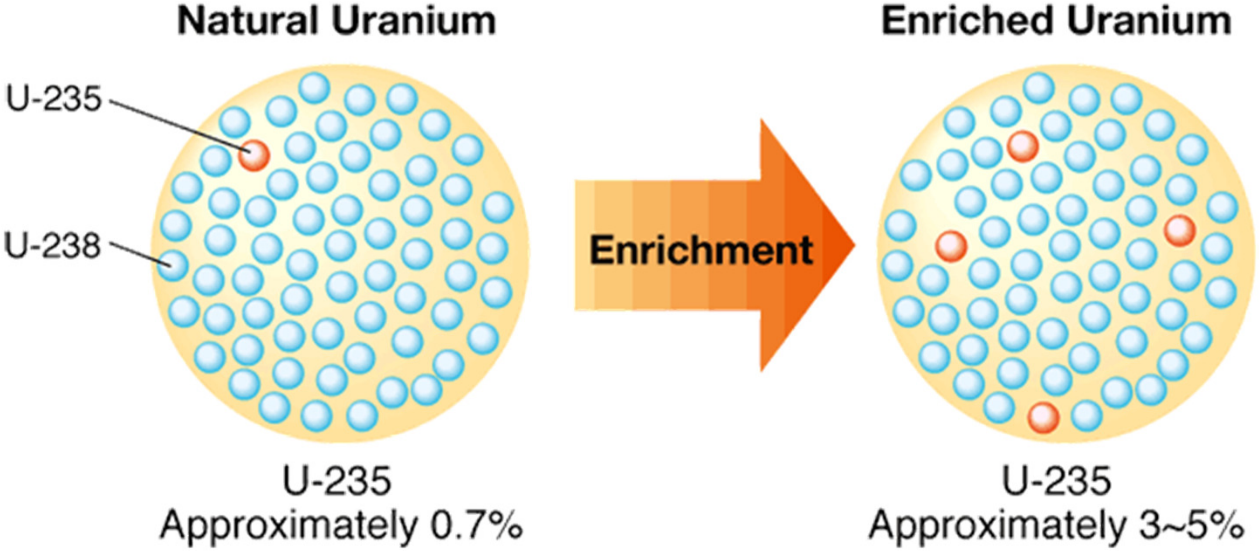


Uranium Enrichment



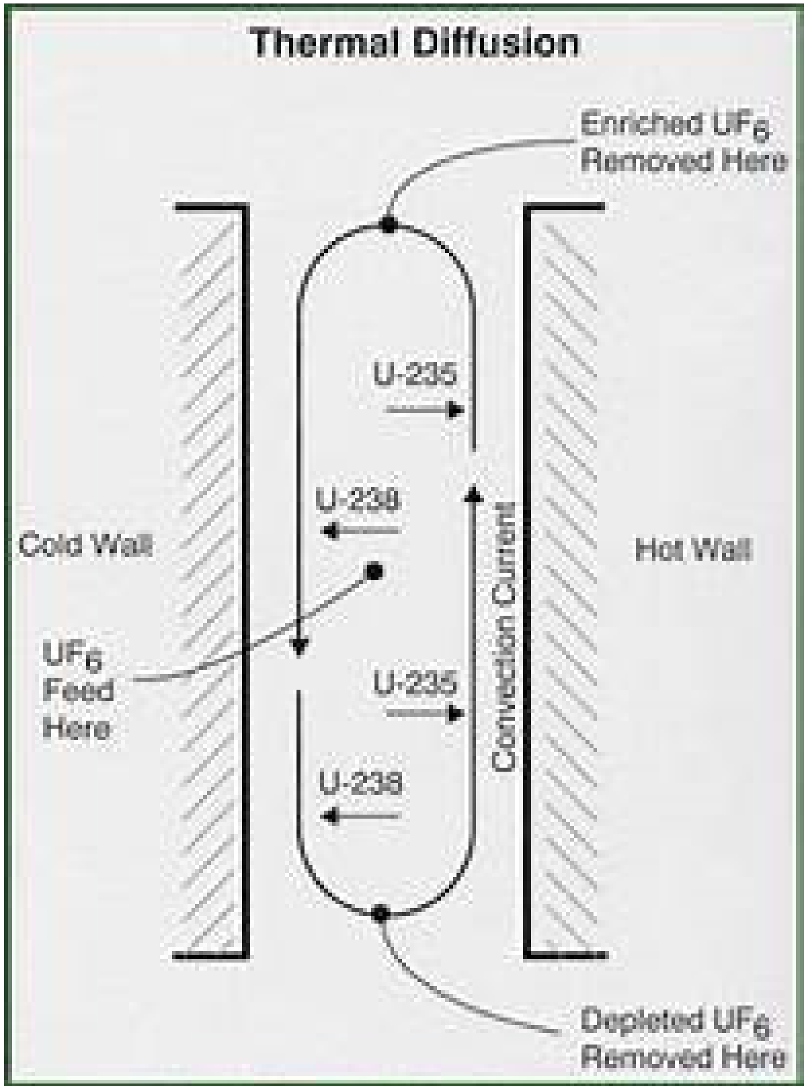
🔵 Uranium-238

🔴 Uranium-235



Enrichment Methods

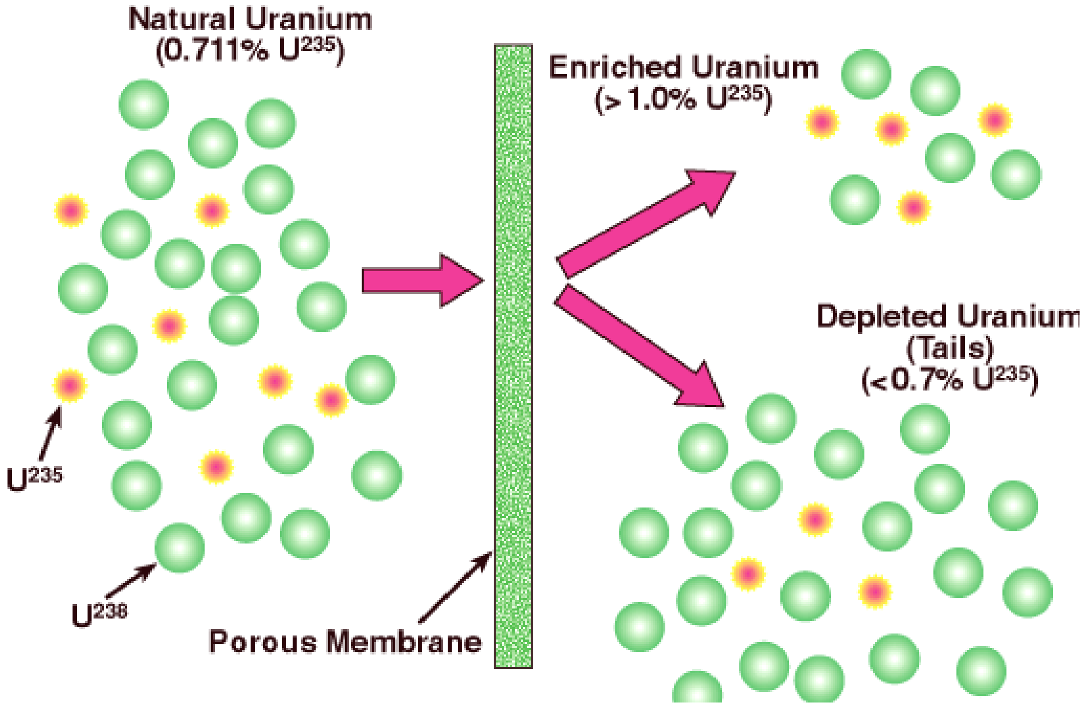
- Thermal Diffusion
- Gaseous Diffusion
- The Gas Centrifuge
- Aerodynamic Process
- Electromagnetic Isotope Separation(EMIS)
- Laser Processes
- Chemical Methods
- Plasma Separation



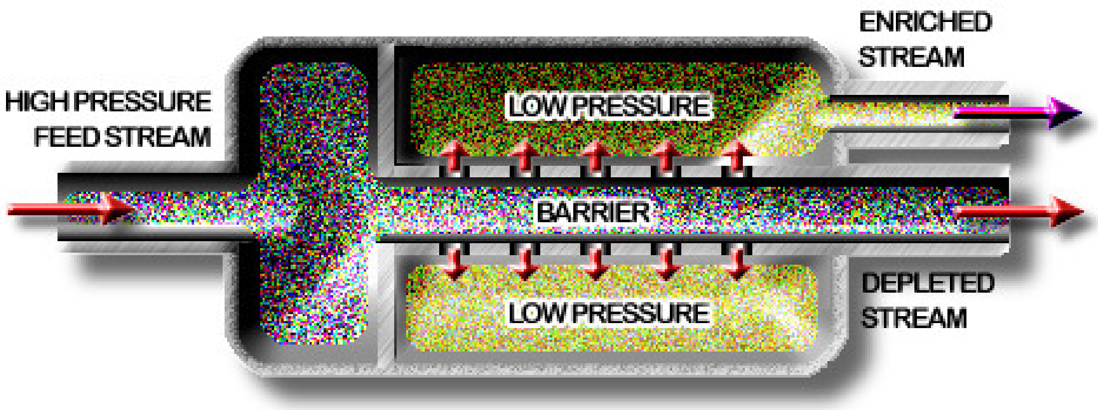
Liquid thermal diffusion method for the enrichment of uranium.

فرآیند انتشار حرارتی بر این اساس استوار است که انتشار مولکولی می تواند توسط یک شیب دما ایجاد شود. به طور کلی ، اگر دو گاز در معرض شیب دما بین دو سطح قرار بگیرند ، گاز با وزن مولکولی پایین تر به سمت گرمتر گرایش پیدا می کند. این دو گاز از هم جدا می شوند تا زمانی که یک شیب غلظت رخ دهد و در نتیجه باعث انتشار غلظت به اندازه مساوی در جهت مخالف می شود. در شرایط تعادل سرعت انتقال مولکول های سبک به سمت سطح گرم حاصل از انتشار حرارتی دقیقاً با انتشار غلظت متعادل خواهد شد. در یک ستون انتشار حرارتی ، عامل جدایی نسبتاً کوچک در اثر جریان های همرفت حاصل از شیب دما ضرب می شود. مولکول های سنگین ، که به سمت سطح سرد تمایل دارند ، به پایین ستون جارو می شوند در حالی که مولکول های سبک در سطح گرم به سمت بالای ستون جاروب می شوند.

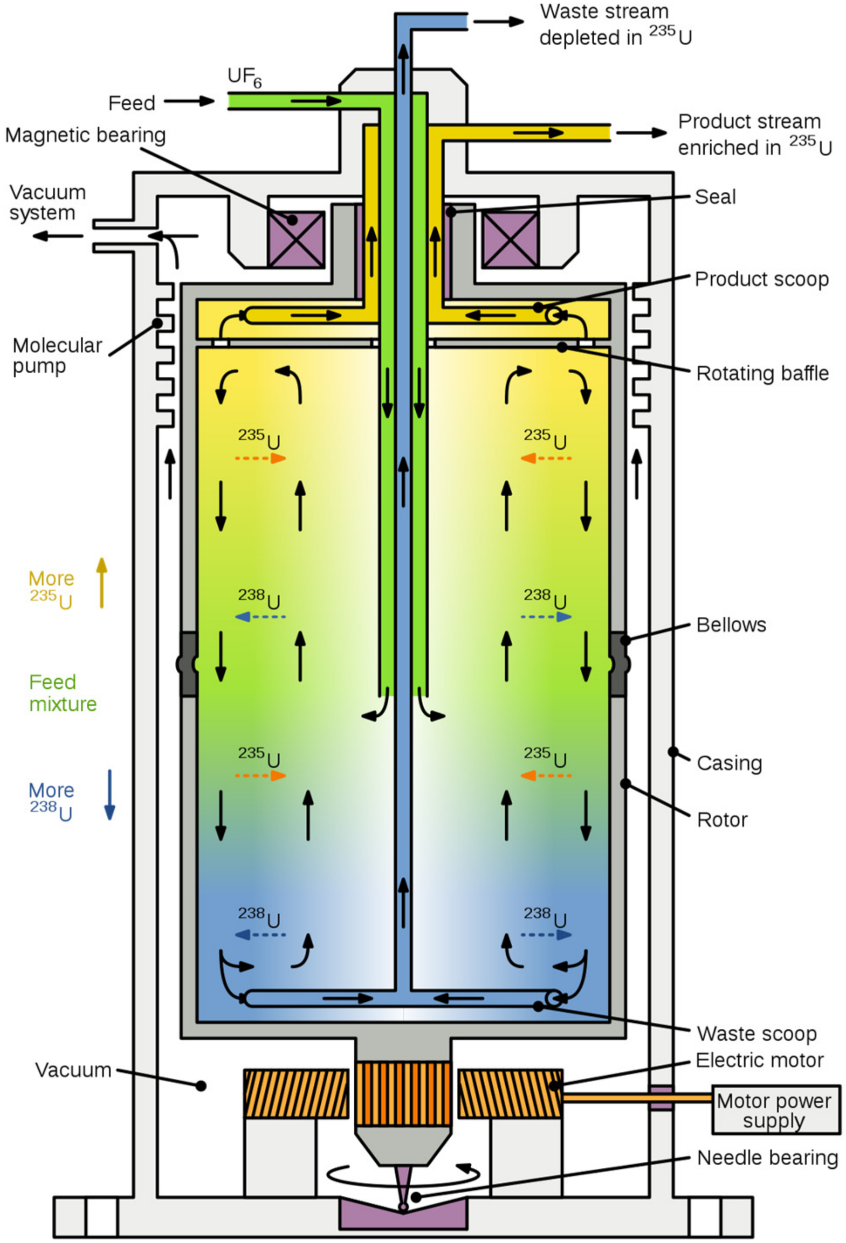
Gaseous Diffusion Uranium Enrichment Process



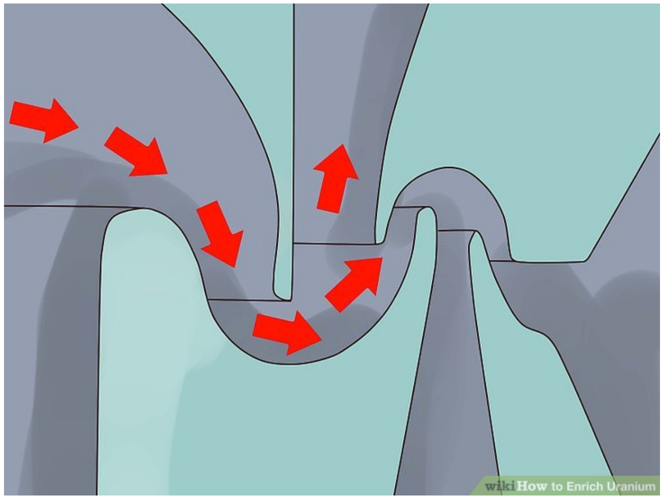
GASEOUS DIFFUSION STAGE

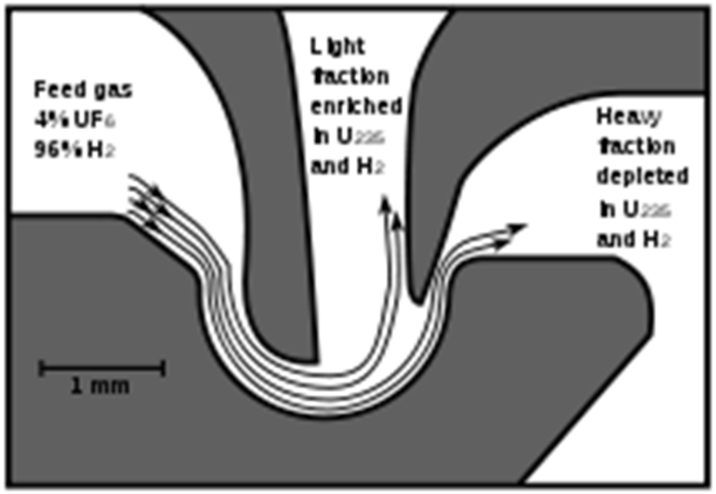


the gas centrifuge

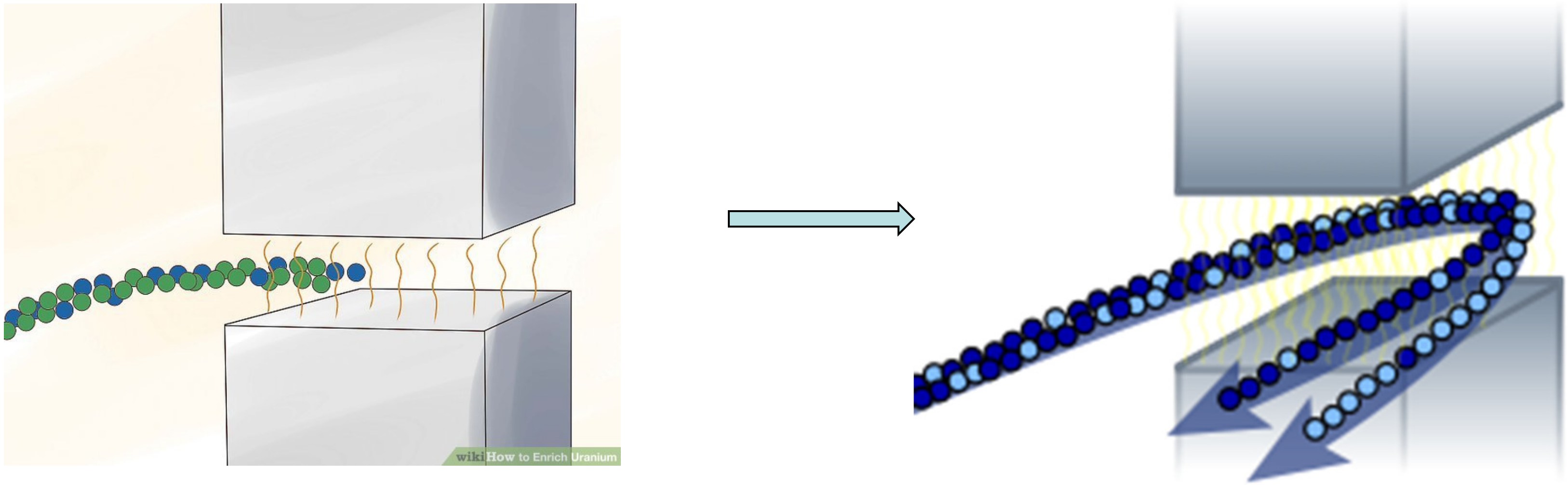


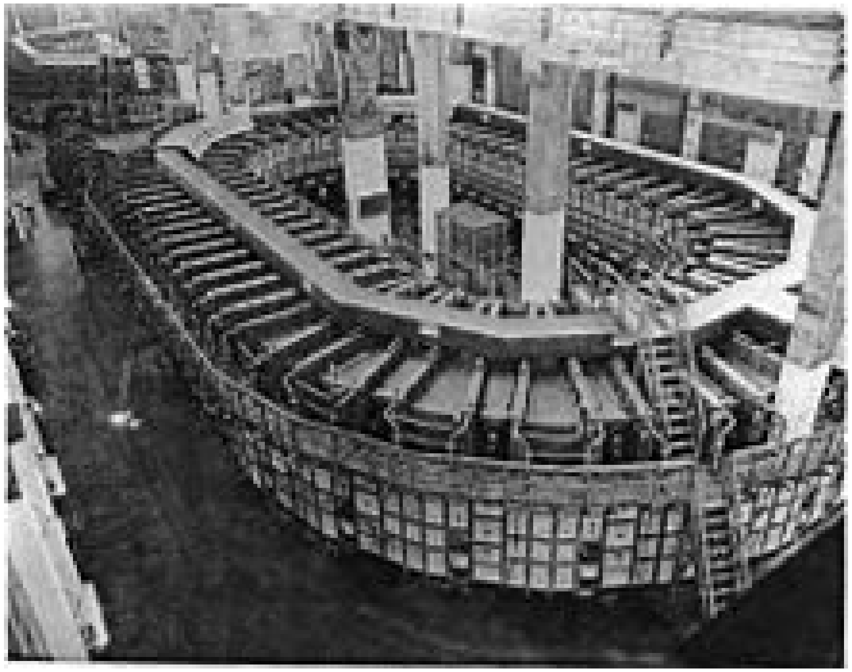
Aerodynamics Separation Process





Electromagnetic Isotope Separation Process

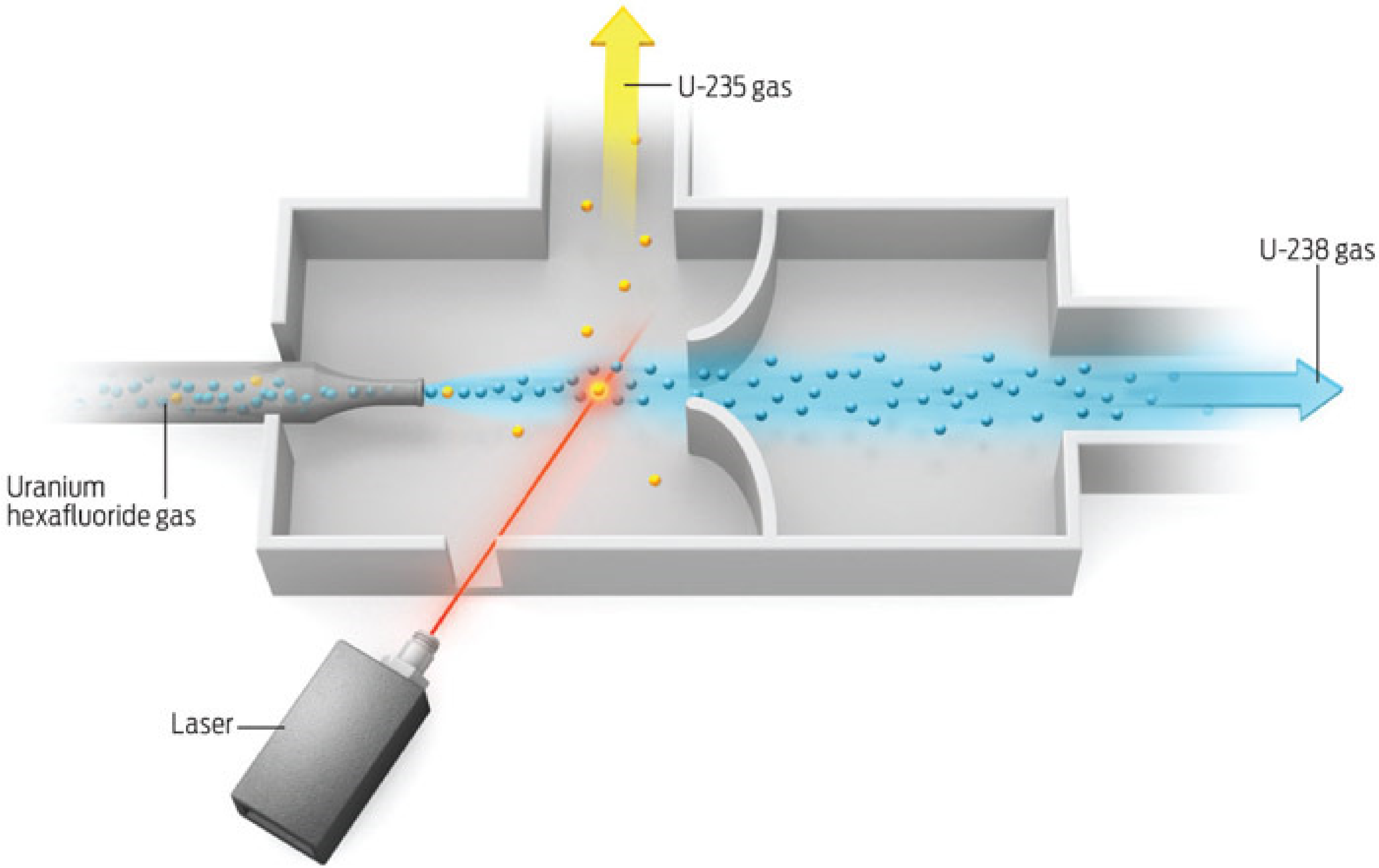


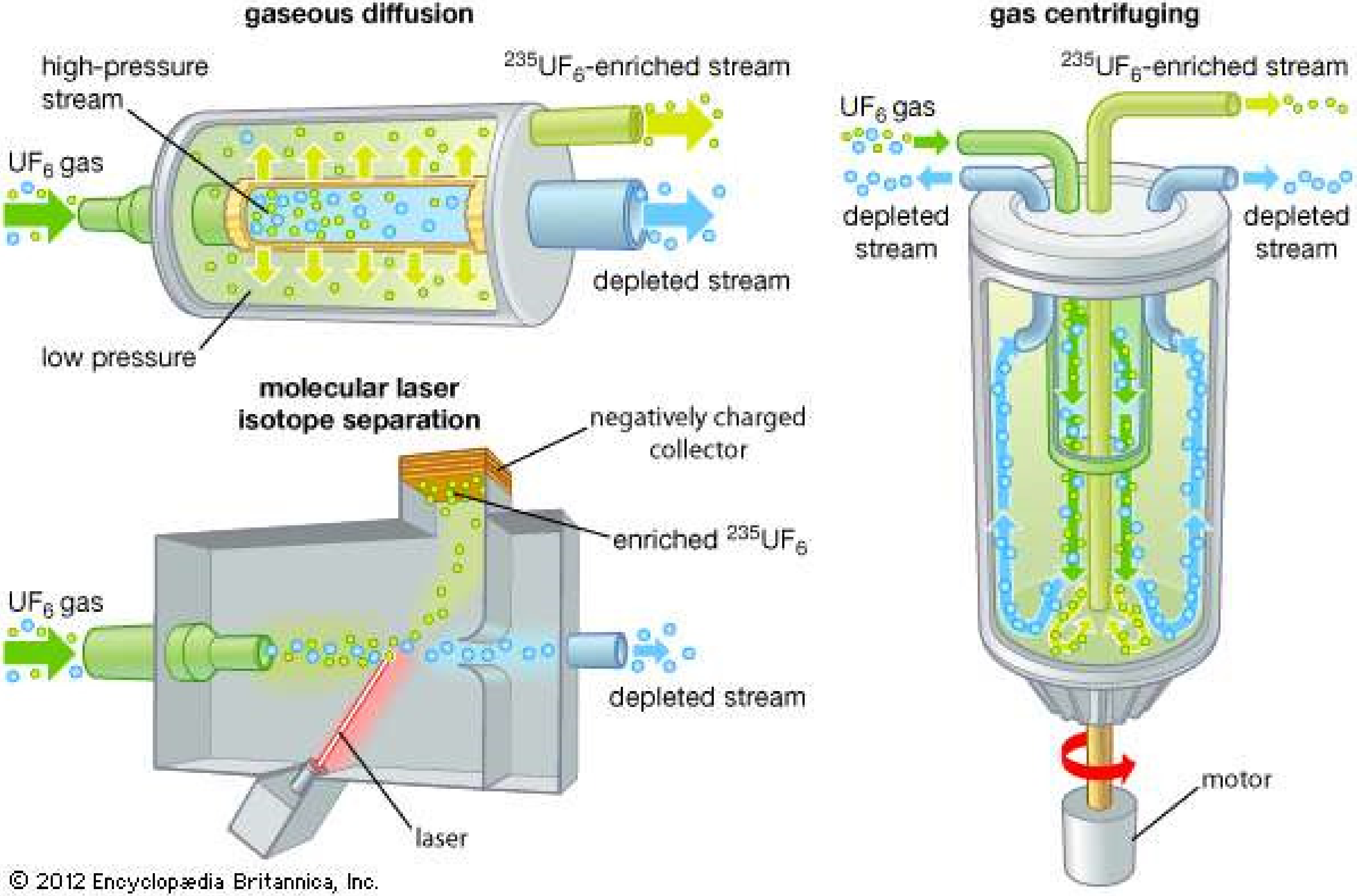


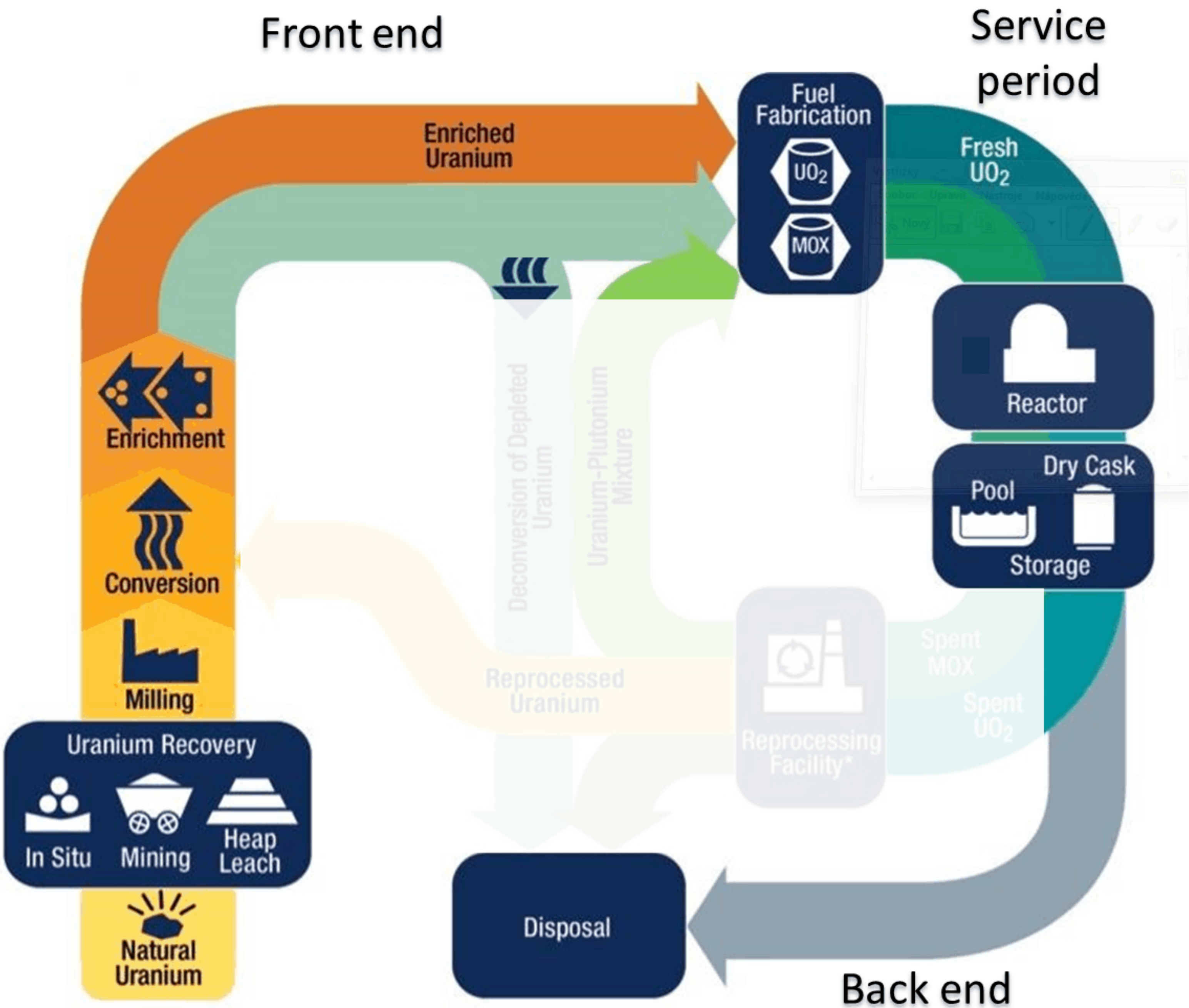
Responsibility for the design and construction of the electromagnetic separation plant, which came to be called Y-12, was assigned to Stone & Webster by the S-1 Committee in June 1942. The design called for five first-stage processing units, known as Alpha racetracks, and two units for final processing, known as Beta racetracks. In September 1943 Groves authorized construction of four more racetracks, known as Alpha II. Construction began in February 1943.

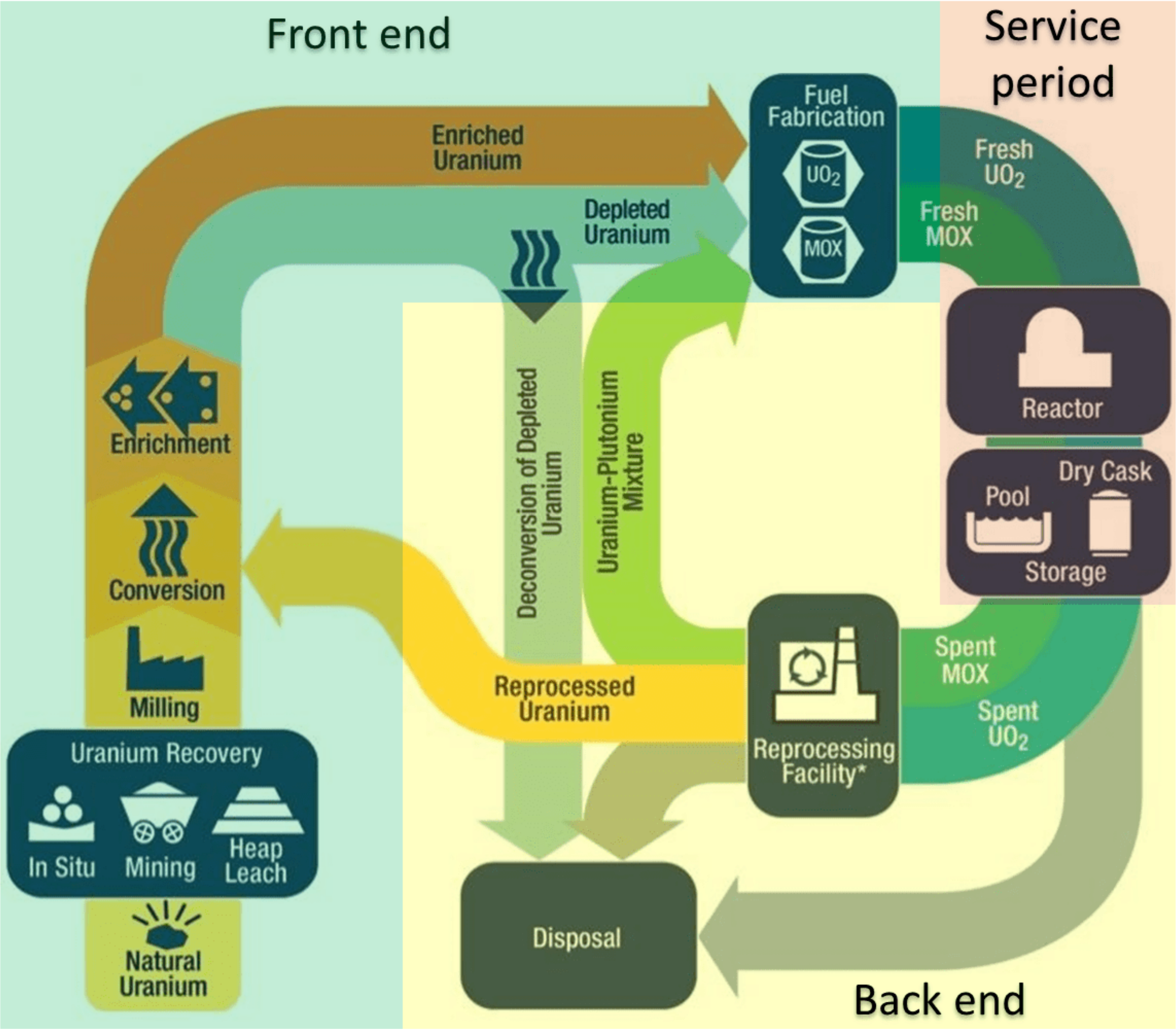
https://en.m.wikipedia.org/wiki/Manhattan_Project

Laser Uranium Enrichment




gaseous diffusion
high-pressure stream
$^{235}UF_6$-enriched stream
UF_6 gas
depleted stream
low pressure
molecular laser isotope separation
negatively charged collector
enriched $^{235}UF_6$
UF_6 gas
depleted stream
laser
gas centrifuging
$^{235}UF_6$-enriched stream
UF_6 gas
depleted stream
depleted stream
motor


Front end
Service period
Back end
Enriched Uranium
Fuel Fabrication
UO2
MOX
Fresh UO2
Reactor
Dry Cask
Pool
Storage
Enrichment
Conversion
Milling
Uranium Recovery
In Situ
Mining
Heap Leach
Natural Uranium
Deconversion of Depleted Uranium
Uranium-Plutonium Mixture
Reprocessed Uranium
Reprocessing Facility*
Spent MOX
Spent UO2
Disposal


Front end
Service period
Back end
Enriched Uranium
Depleted Uranium
Fuel Fabrication
UO2
MOX
Fresh UO2
Fresh MOX
Reactor
Pool
Dry Cask
Storage
Spent MOX
Spent UO2
Reprocessing Facility*
Reprocessed Uranium
Deconversion of Depleted Uranium
Uranium-Plutonium Mixture
Disposal
Enrichment
Conversion
Milling
Uranium Recovery
In Situ
Mining
Heap Leach
Natural Uranium

While uranium is used almost entirely for making electricity, a small proportion is used for the important task of producing medical isotopes. Some is also used in marine propulsion, especially naval.

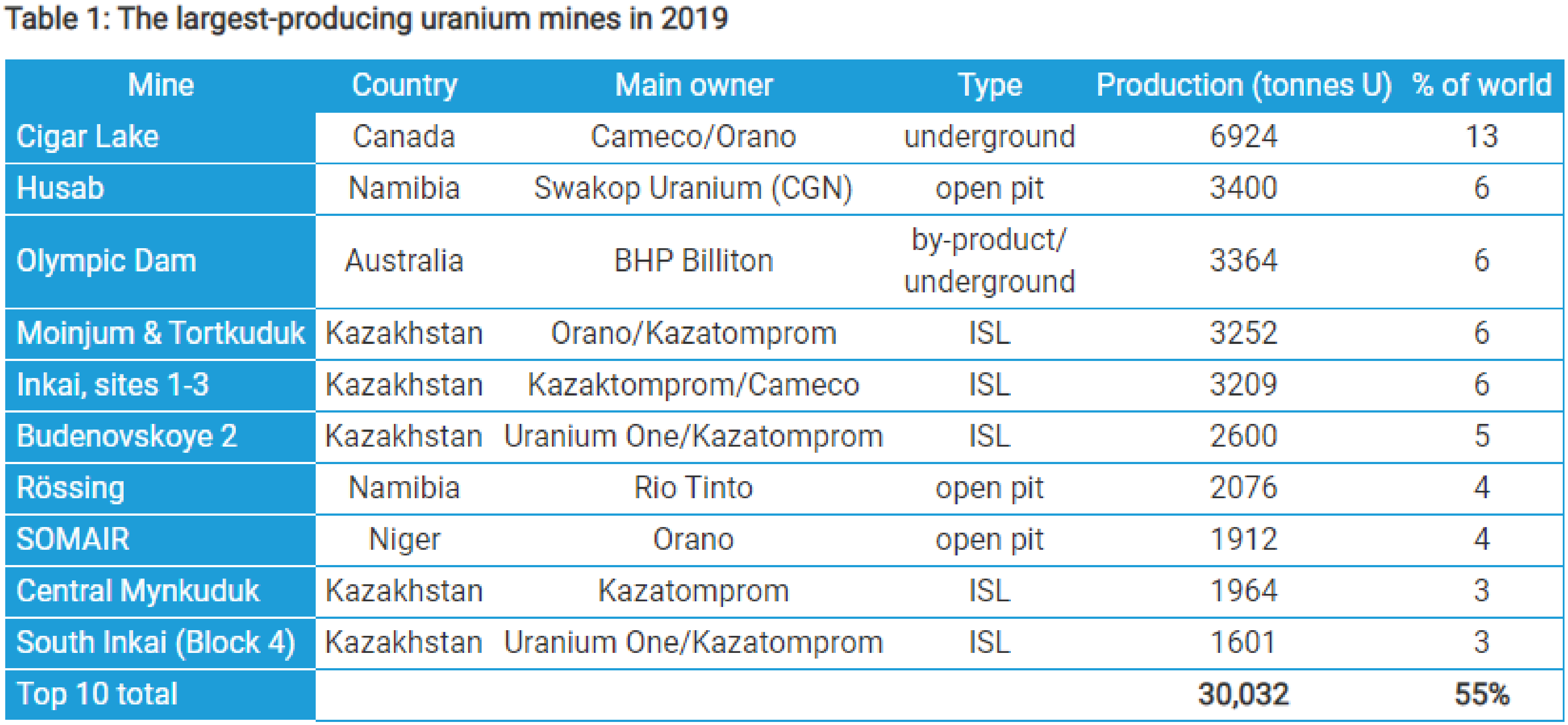


Table 1: The largest-producing uranium mines in 2019

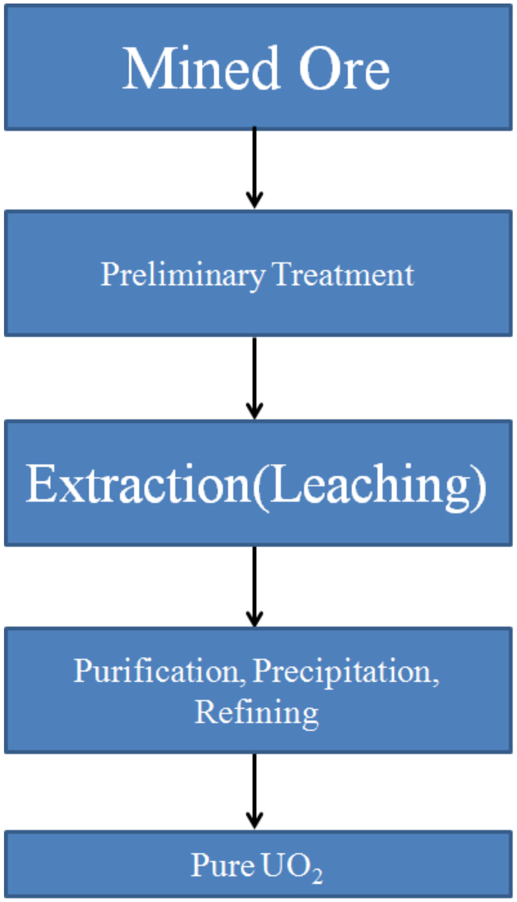
Mine	Country	Main owner	Type	Production (tonnes U)	% of world
Cigar Lake	Canada	Cameco/Orano	underground	6924	13
Husab	Namibia	Swakop Uranium (CGN)	open pit	3400	6
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3364	6
Moinjum & Tortkuduk	Kazakhstan	Orano/Kazatomprom	ISL	3252	6
Inkai, sites 1-3	Kazakhstan	Kazaktomprom/Cameco	ISL	3209	6
Budenovskoye 2	Kazakhstan	Uranium One/Kazatomprom	ISL	2600	5
Rössing	Namibia	Rio Tinto	open pit	2076	4
SOMAIR	Niger	Orano	open pit	1912	4
Central Mynkuduk	Kazakhstan	Kazatomprom	ISL	1964	3
South Inkai (Block 4)	Kazakhstan	Uranium One/Kazatomprom	ISL	1601	3
Top 10 total				**30,032**	**55%**

ISL mining means that removal of the uranium minerals is accomplished without any major ground disturbance.

average grades in excess of 0.10% of uranium

Canadian mines have huge amounts of ore up to 20% U average grade

Other mines however can operate successfully with very low grade ores, down to about 0.02% U. Uranium mines operate in some 20 countries, though in 2019 over 50% of world production came from just nine mines in four countries



Acid Leaching Reactions

$$UO_2 + 2\,Fe^{3+} = UO_2^{2+} + 2Fe^{2+}$$

$$UO_3 + 2H^+ = UO_2^{2+} + H_2O$$

$$UO_2^{2+} + 3SO_4^{2-} = [UO_2(SO_4)_3]^{4-}$$

Alkaline Leaching Reactions

$$2UO_2 + O_2 = 2UO_3$$

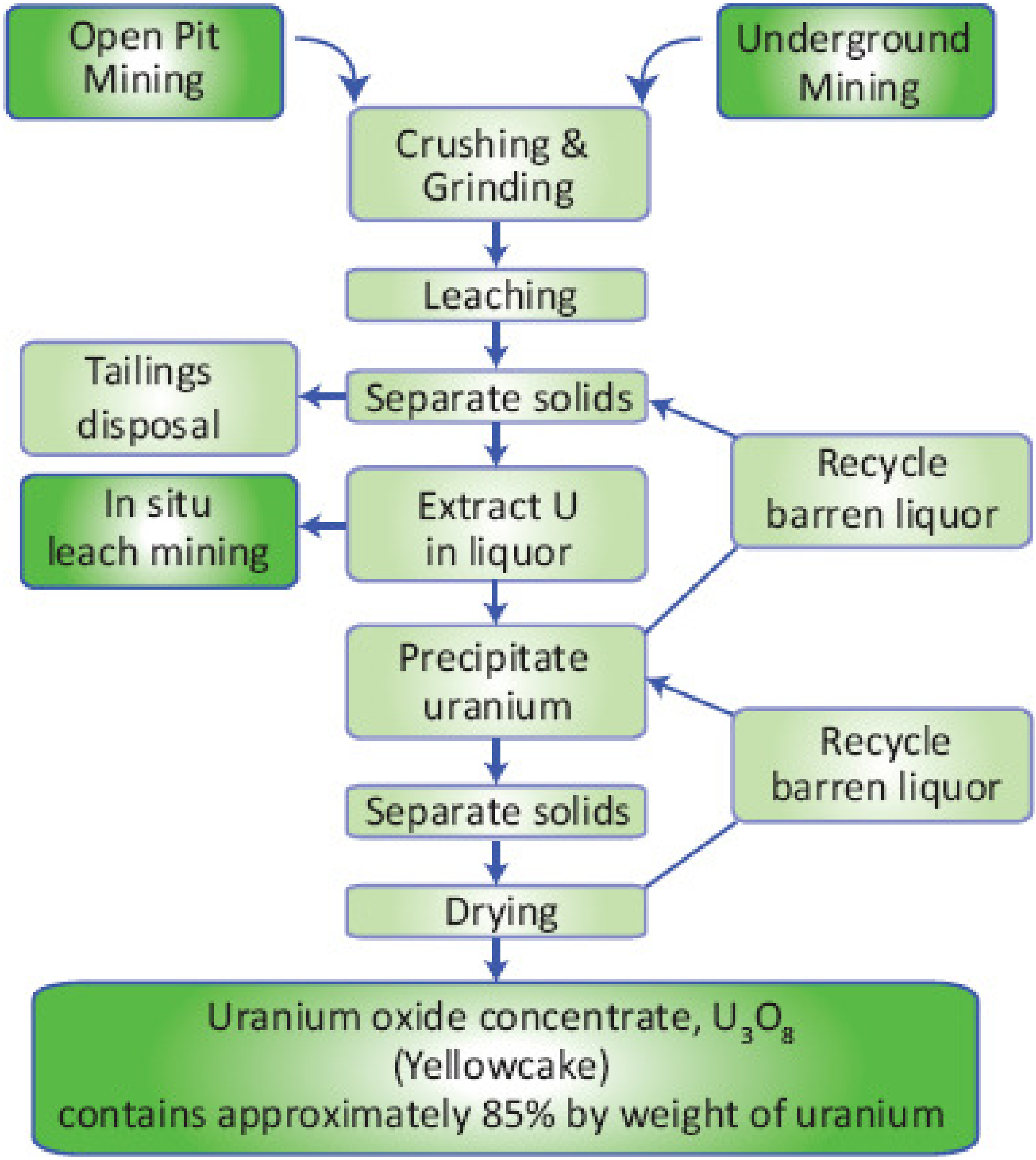
$$UO_3 + Na_2CO_3 + 2NaHCO_3 = Na_4UO_2(CO_3)^3 + H_2O$$

$$UO_3 + 3Na_2CO_3 + H_2O = Na_4UO_2(CO_3)^3 + 2NaOH$$

Fig. 2: Process scheme for uranium mining and processing to produce useable uranium product, including chemical equations for acid and alkaline leaching process

U_3O_8 product,

which is the form in which uranium is marketed and exported



Open Pit Mining

Underground Mining

Crushing & Grinding

Leaching

Tailings disposal

Separate solids

Recycle barren liquor

In situ leach mining

Extract U in liquor

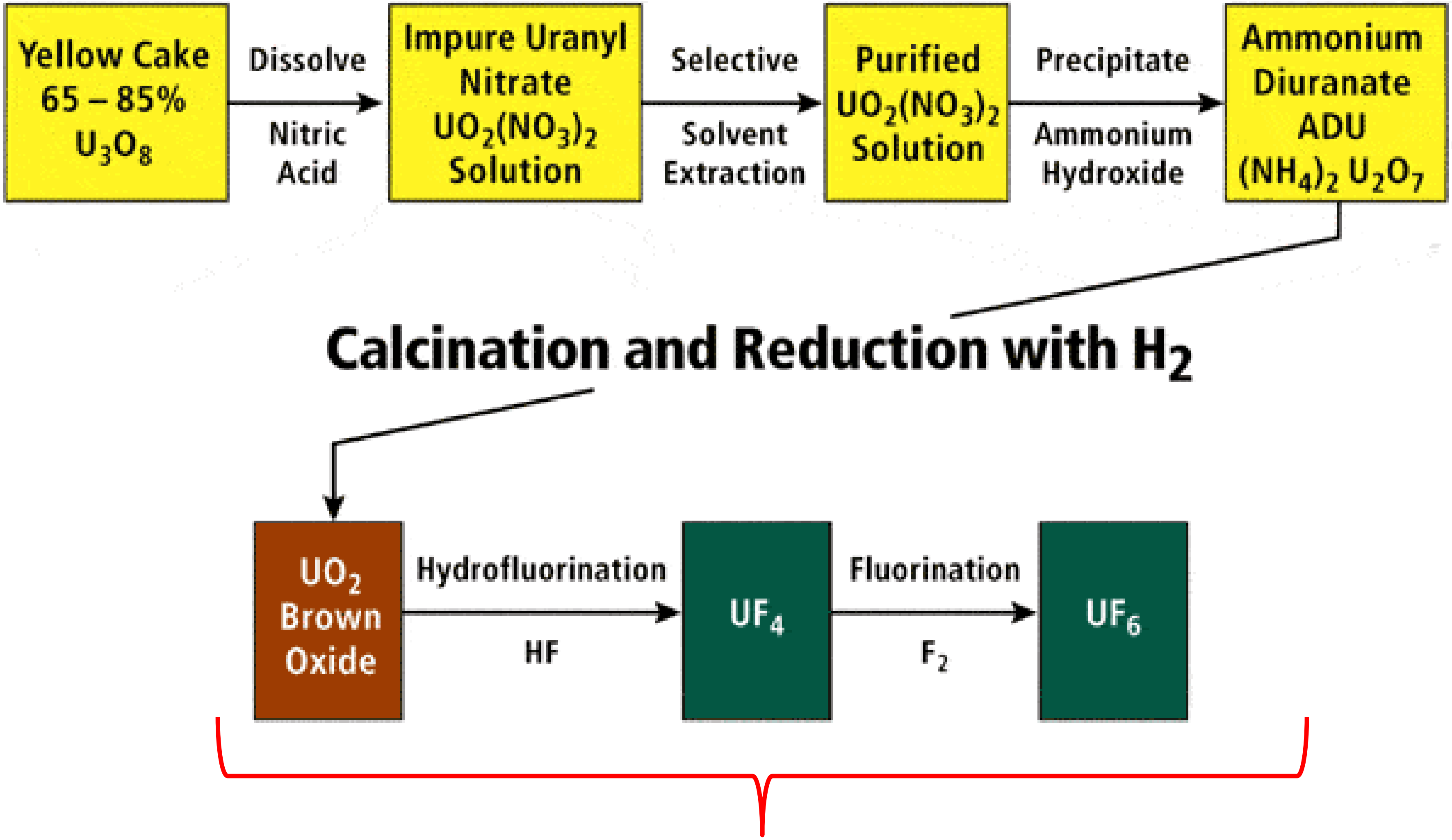
Precipitate uranium

Recycle barren liquor

Separate solids

Drying

Uranium oxide concentrate, U_3O_8
(Yellowcake)
contains approximately 85% by weight of uranium



Yellow Cake 65 – 85% U_3O_8

Dissolve → Nitric Acid

Impure Uranyl Nitrate $UO_2(NO_3)_2$ Solution

Selective → Solvent Extraction

Purified $UO_2(NO_3)_2$ Solution

Precipitate → Ammonium Hydroxide

Ammonium Diuranate ADU $(NH_4)_2\,U_2O_7$

Calcination and Reduction with H_2

UO_2 Brown Oxide

Hydrofluorination → HF

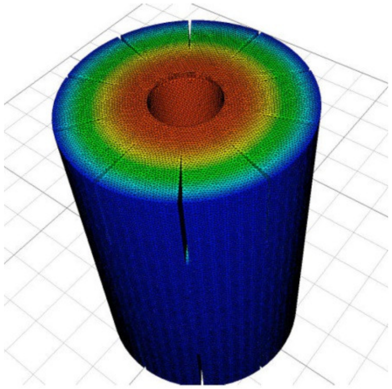
UF_4

Fluorination → F_2

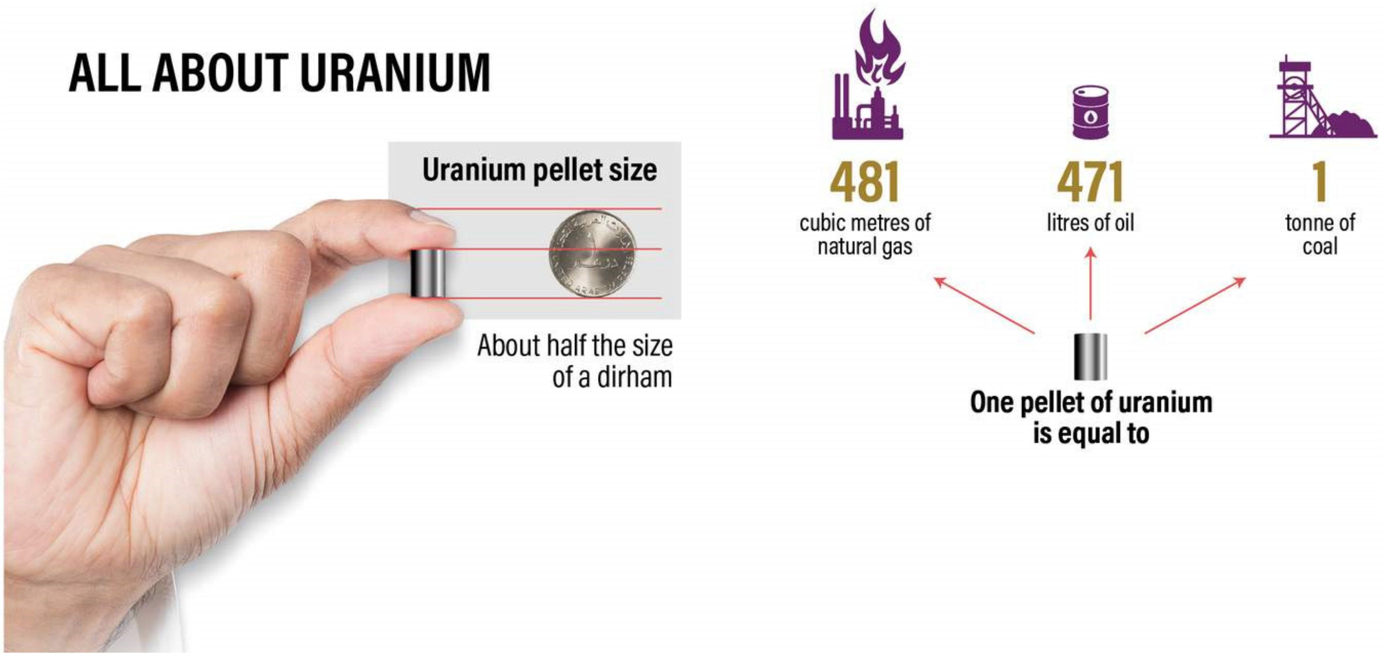
UF_6

غنی سازی

- Reacts with water
  - $UF_6 + 2H_2O \longleftrightarrow UO_2F_2 + 4HF$
- Metallic uranium preparation
  - UF_4 or UCl_4 with Ca or Mg
  - UO_2 with Ca
  - Electrodeposition from molten salt baths

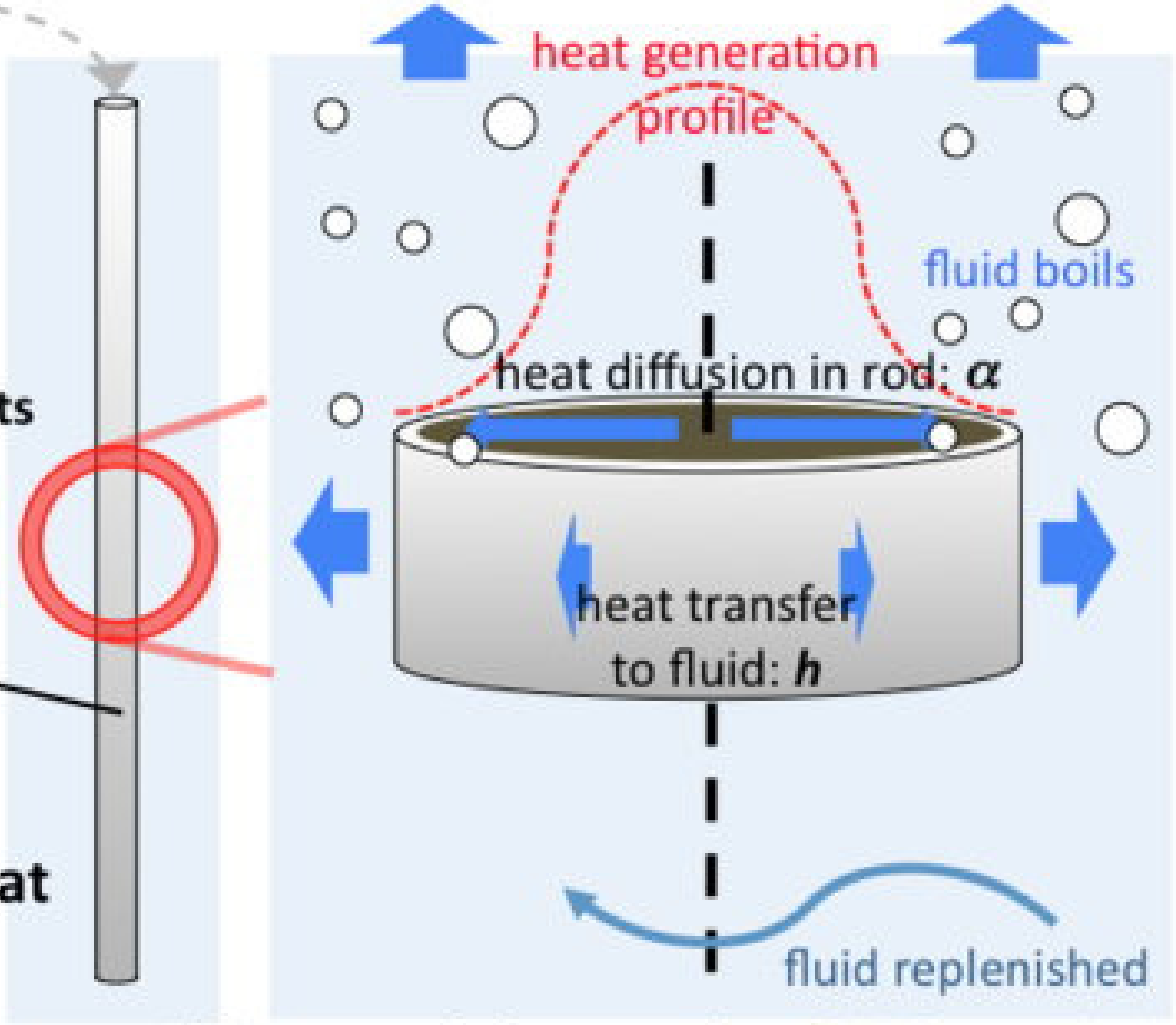


تبدیل UF6 به اکسید اورانیوم و در نهایت تبدیل به قرص های استوانه ای کوچک. با توجه به ضریب انتقال حرارت هدایتی پایین این قرصها مواد پایه سرامیک و یا فلزی اضاف می شود تا دمای مرکز آنها بواسطه افزایش ضریب انتقال حرارت هدایتی کاهش یابد



Nuclear Fuel Rods

UOX or MOX pellets
melt at
3000 °C



Zircaloy rod
melts at
2200 °C

rod makes heat

heat leaves
via steam

heat generation
profile

fluid boils

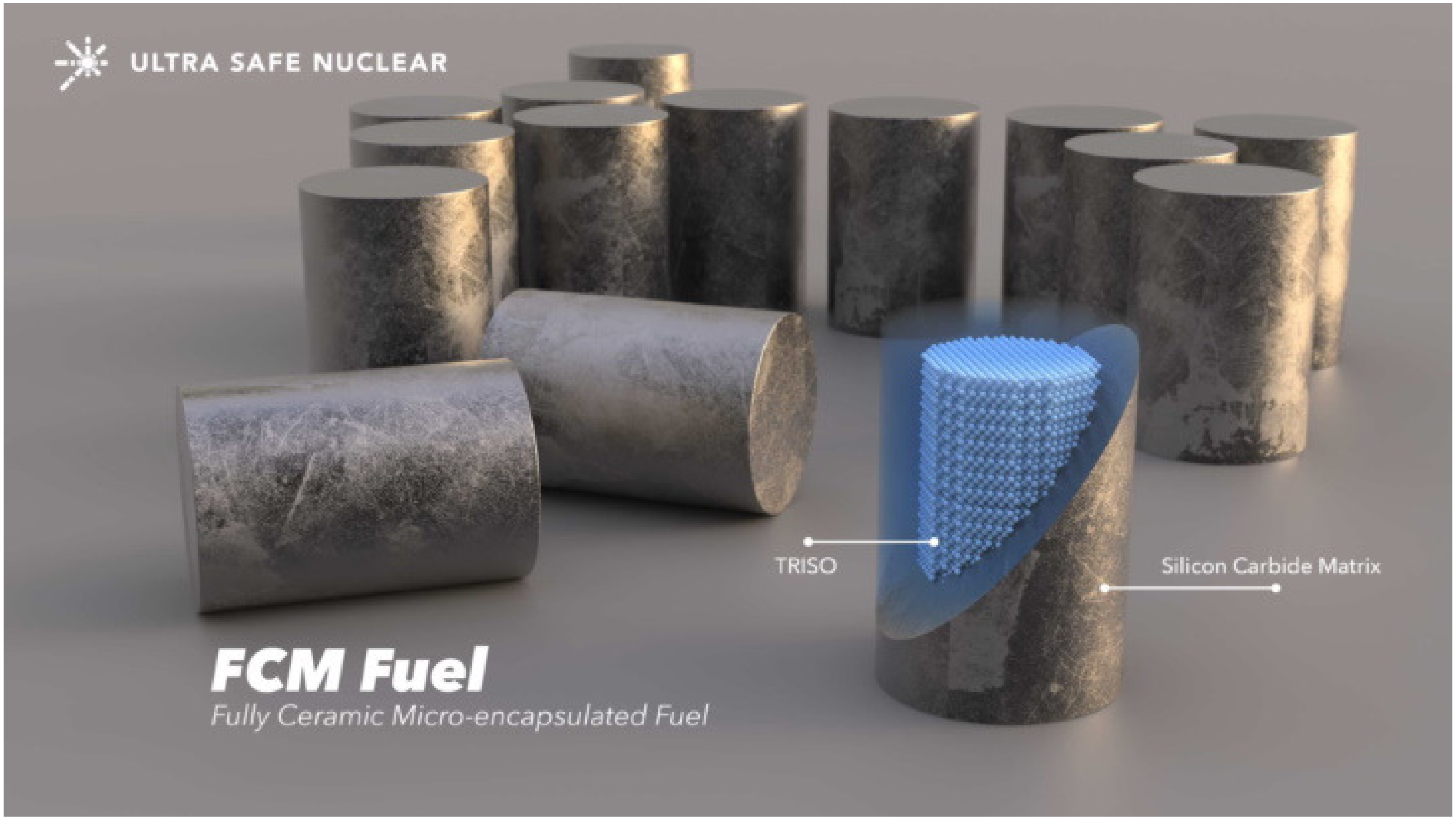
heat diffusion in rod: α

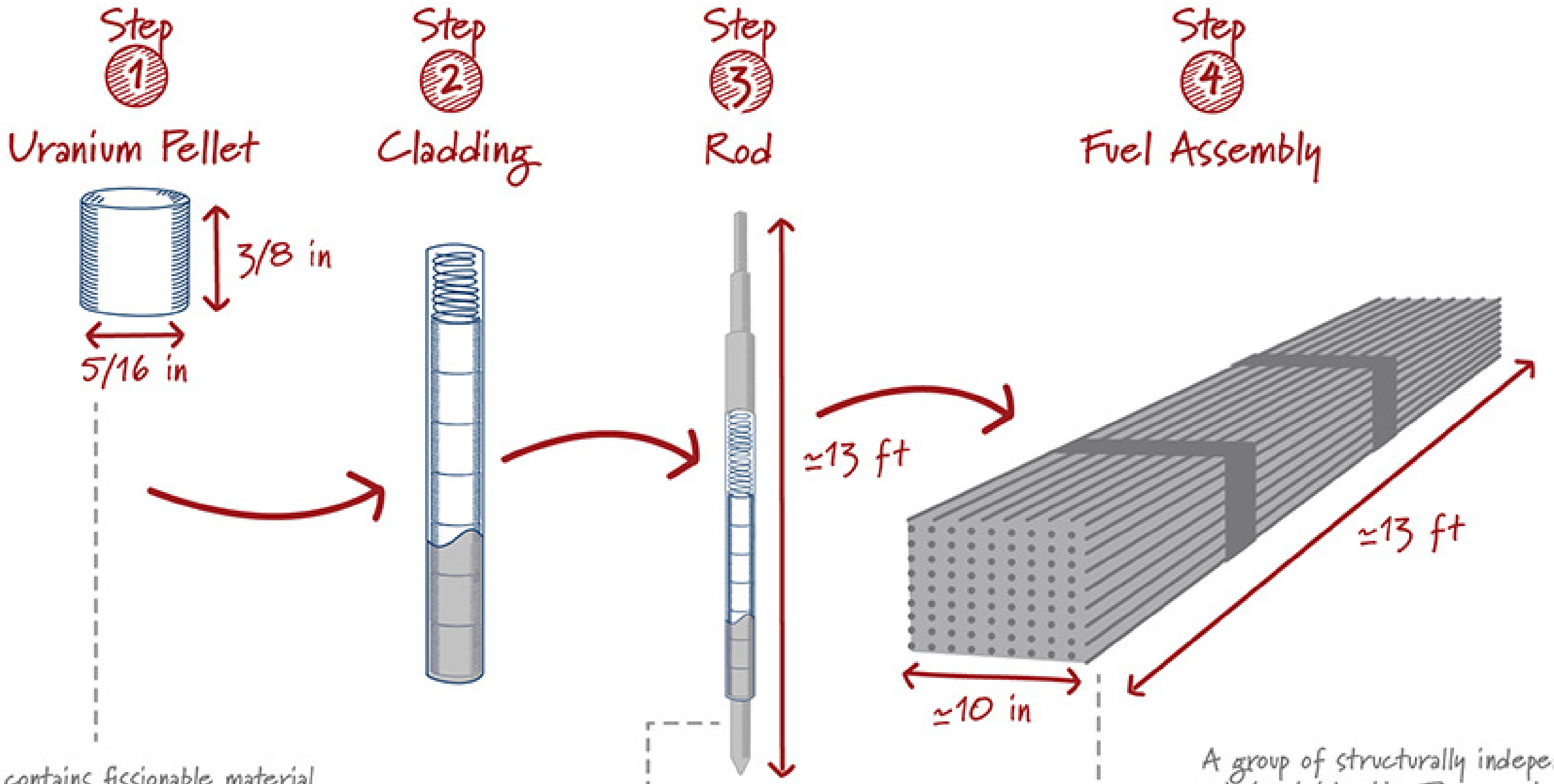
heat transfer
to fluid: h

fluid replenished

if **heat path** from rod to fluid to exit is
interrupted, temperature will rise

USNC describes FCM as a next-generation uranium oxycarbide tristructural isotropic (TRISO) particle fuel design, replacing the 50-year-old graphite matrix of traditional TRISO fuel with silicon carbide (SiC). It says the result is a safer nuclear fuel that can withstand higher temperatures and more radiation. The SiC matrix in FCM fuel provides a dense, gas-tight barrier preventing the escape of fission products, even if a TRISO particle should rupture during operation. The new matrix improves the structural and containment characteristics of TRISO particles, trapping and sealing radioactive fission products permanently, preventing contamination of the environment. The higher-thermal conductivity of FCM fuel allows the fuel pellet to have a flatter temperature profile, lowering peak temperatures in nuclear reactors.

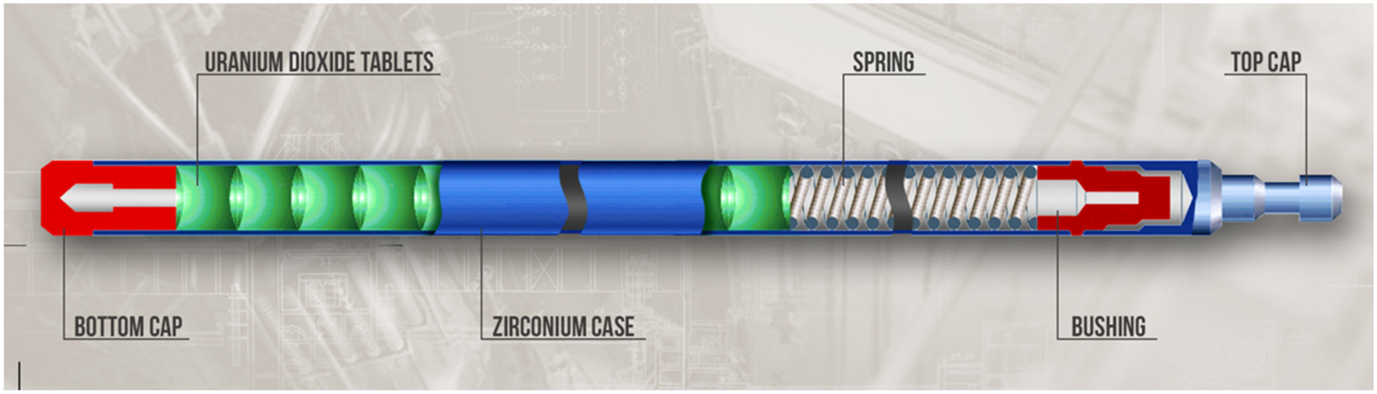


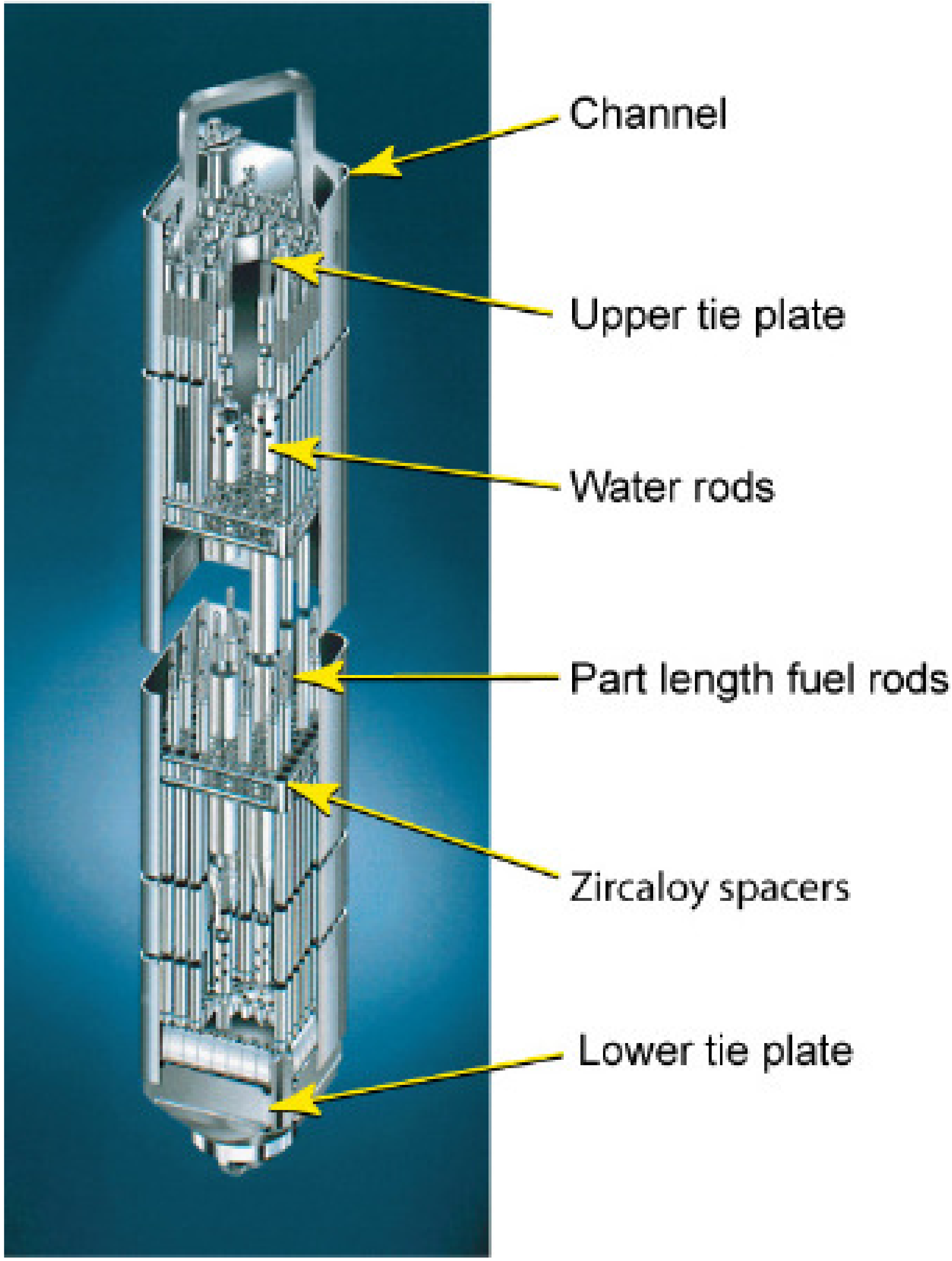


It contains fissionable material (U-235) in the form of enriched ceramic UO_2, where the chain reaction fission is produced.

Built with zirconium alloy. It encapsulates the pellets and ensures their hermeticism.

A group of structurally independent rods in rigid units. The reactor core in a 1,000 MWe plant is composed of approcimately 150 fuel assemblies.





Channel

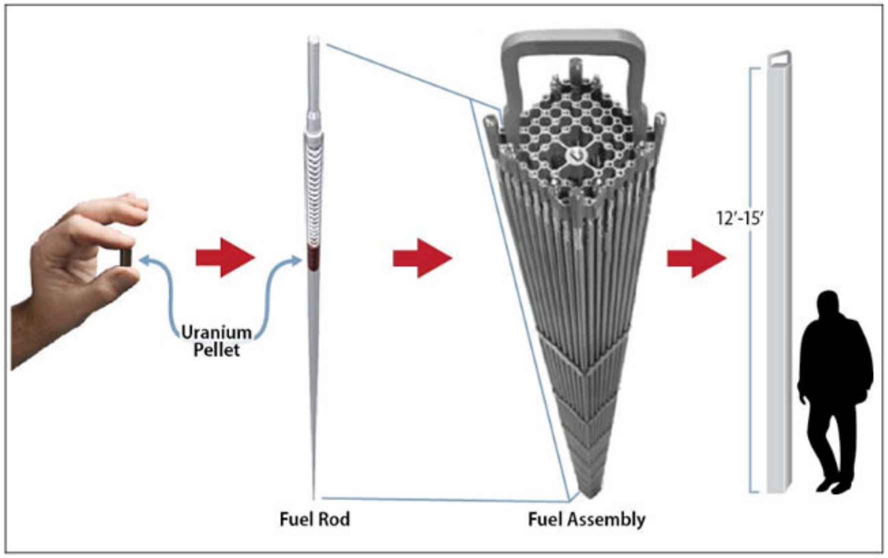
Upper tie plate

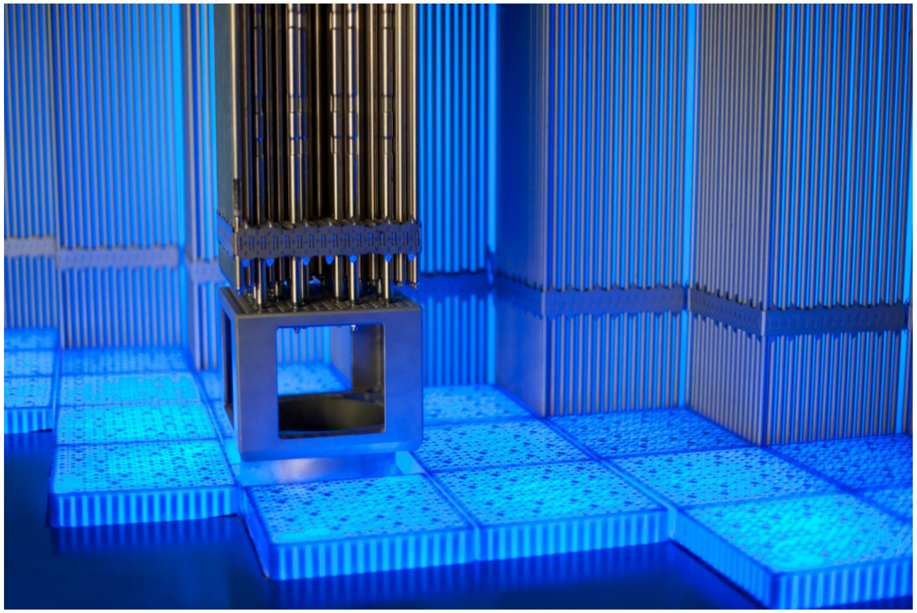
Water rods

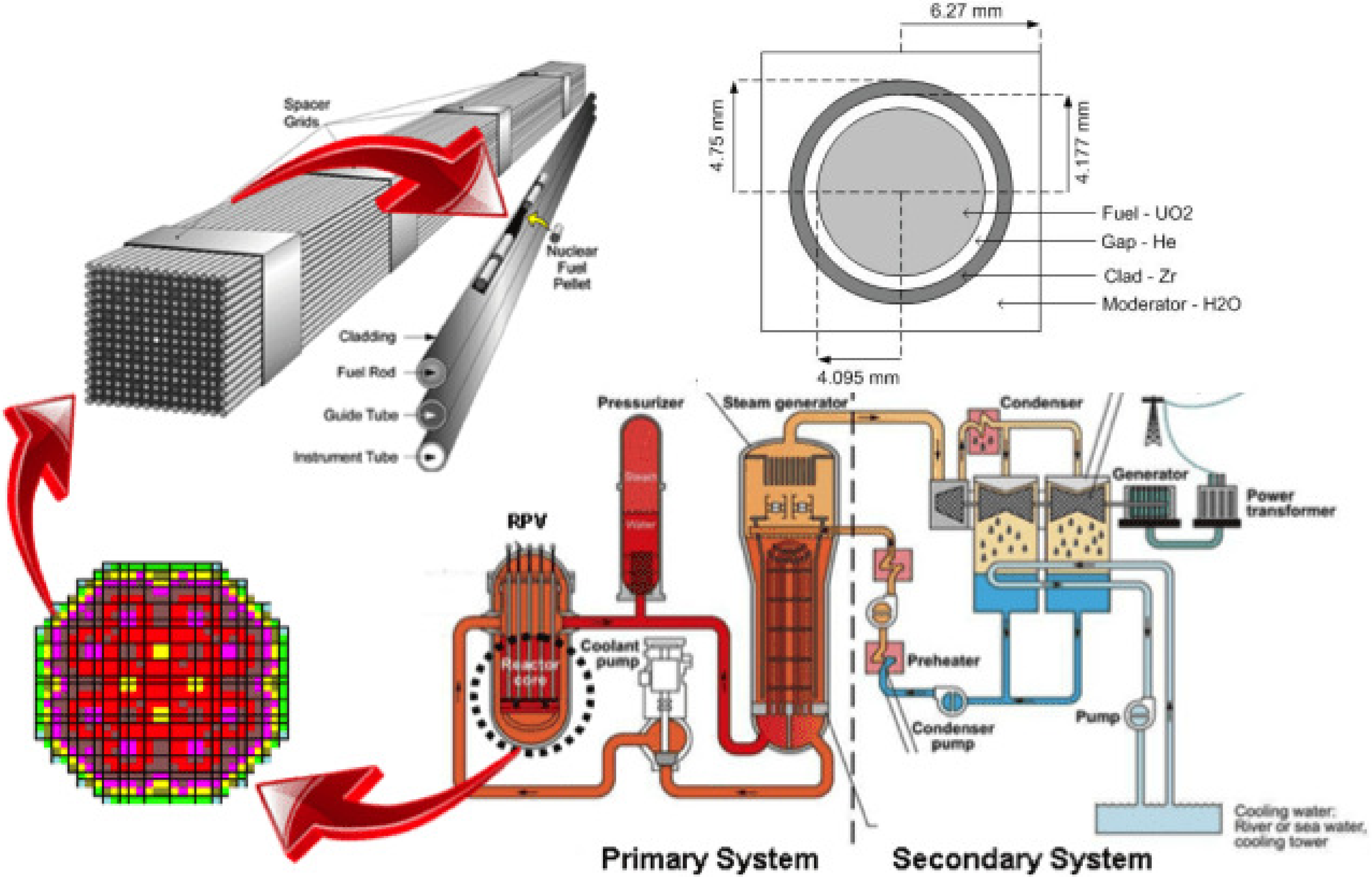
Part length fuel rods

Zircaloy spacers

Lower tie plate





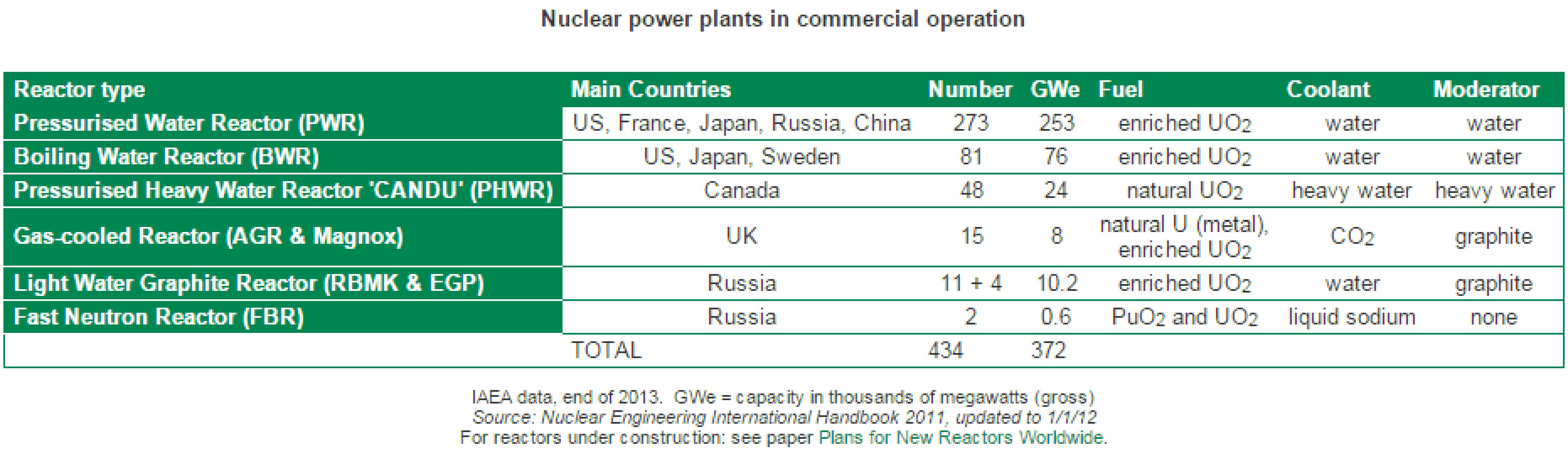

6.27 mm
4.75 mm
4.177 mm
Fuel - UO2
Gap - He
Clad - Zr
Moderator - H2O
4.095 mm
Spacer Grids
Nuclear Fuel Pellet
Cladding
Fuel Rod
Guide Tube
Instrument Tube
Pressurizer
Steam
Water
Steam generator
Condenser
Generator
Power transformer
RPV
Reactor core
Coolant pump
Preheater
Condenser pump
Pump
Cooling water: River or sea water, cooling tower
Primary System
Secondary System

Main Components Of A Reactor

- Fuel Rods – Tube filled with pellets of Uranium
- Shielding - Protection against alpha, beta and Gamma Rays
- Moderator - Slow down the neutron release(Heavy water, Beryllium, Graphite)
- Control Rods - neutron absorbing material(boron Carbide, cadmium)
- Coolant - To transfer the heat generated inside the reactor to a heat exchanger for utilization of power generation
- Steam Separator - steam from the heated coolant is fed to the turbines to produce electricity from generator.
- Containment - concrete lined cavity acting as a radiation shield

Types of Nuclear Reactors

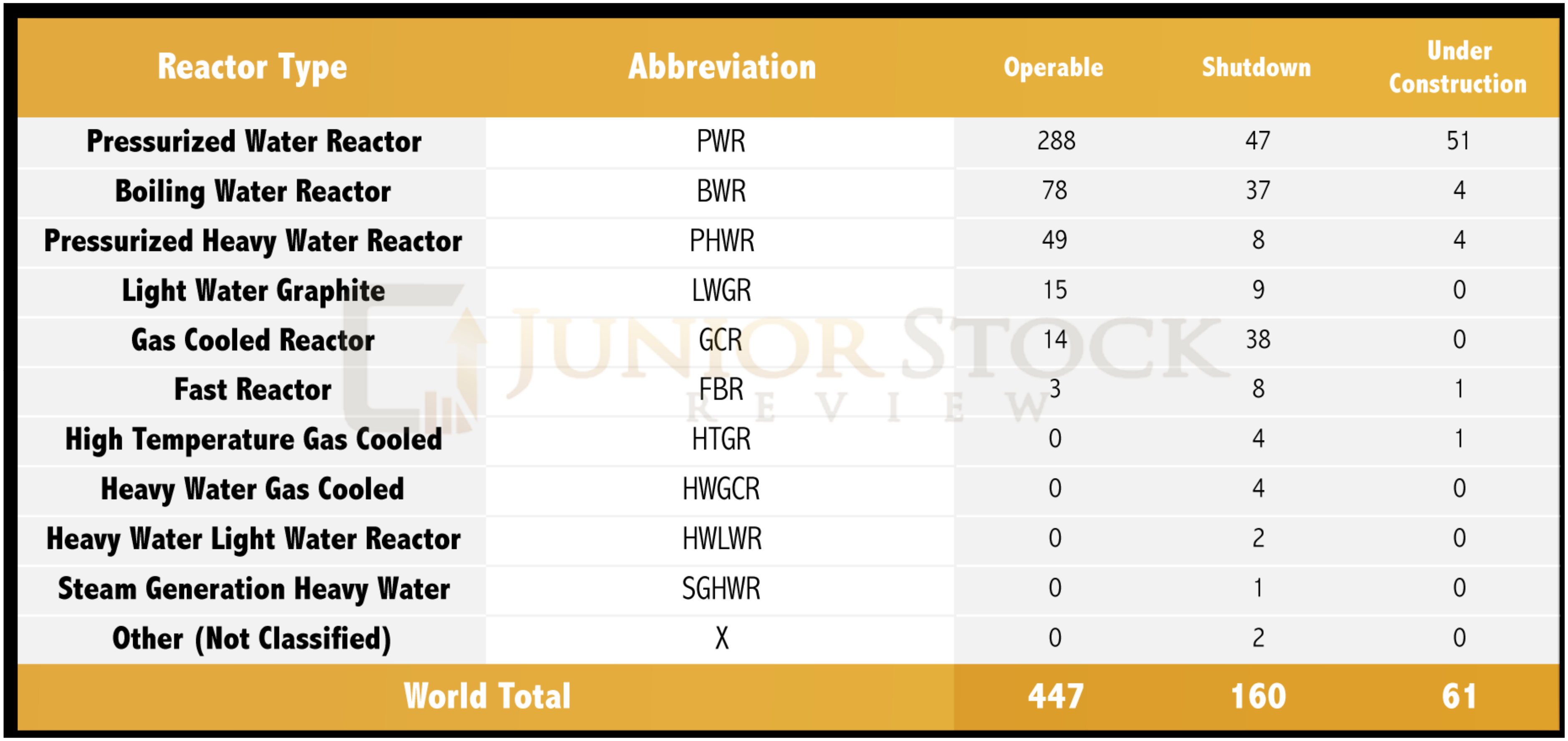
1. BWR-Boiling Water Reactor
2. PWR-Pressurized Water Reactor
3. PHWR-Pressurised Heavy Water Reactor
4. GCR-Gas Cooled Reactor
5. AGR-Advanced Gas-Cooled Reactor
6. LGR-Light Water Cooled - Graphite Moderated Reactor



Nuclear power plants in commercial operation

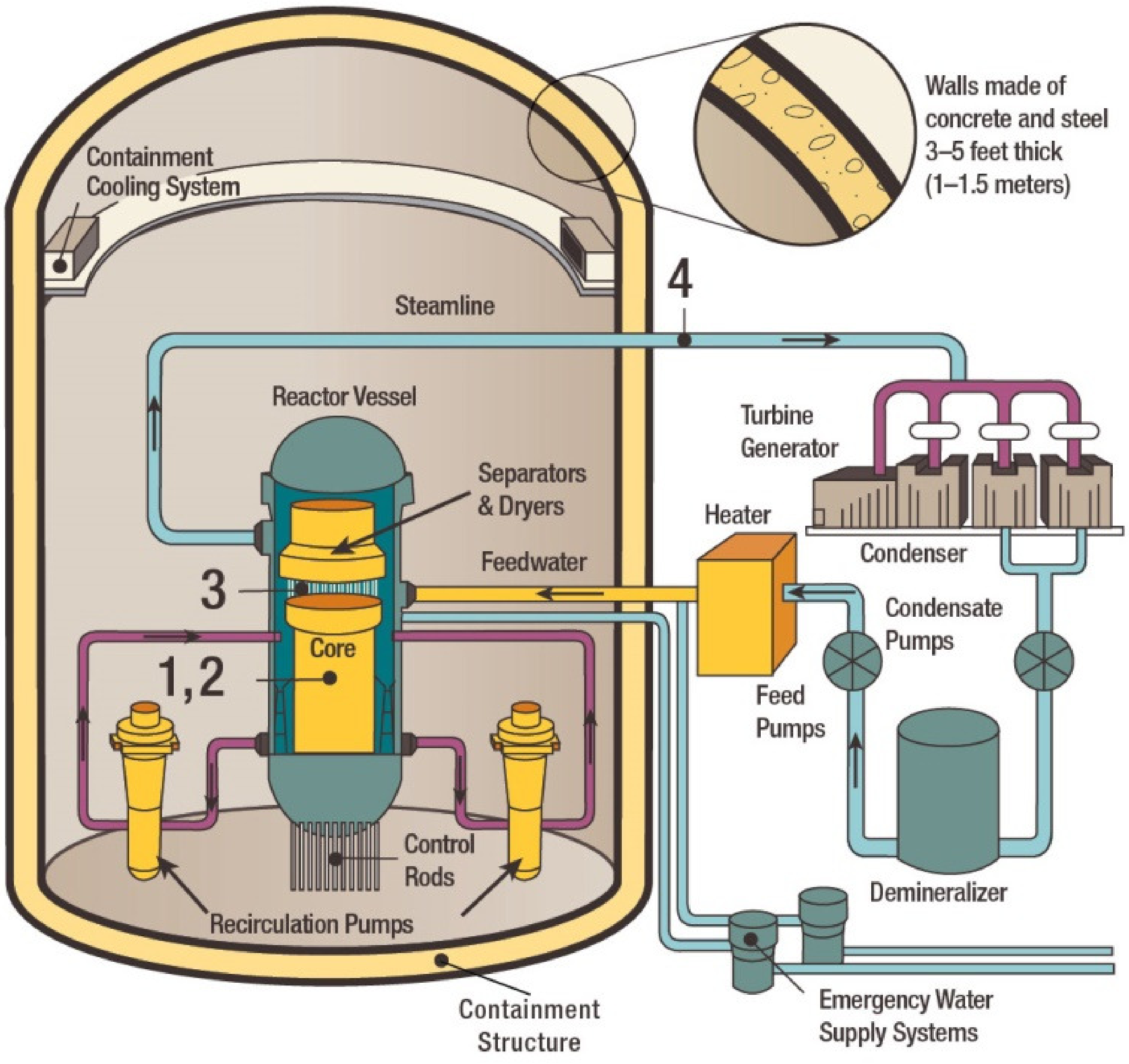
Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia, China	273	253	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	81	76	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	48	24	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	15	8	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK & EGP)	Russia	11 + 4	10.2	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Russia	2	0.6	PuO_2 and UO_2	liquid sodium	none
	TOTAL	434	372			

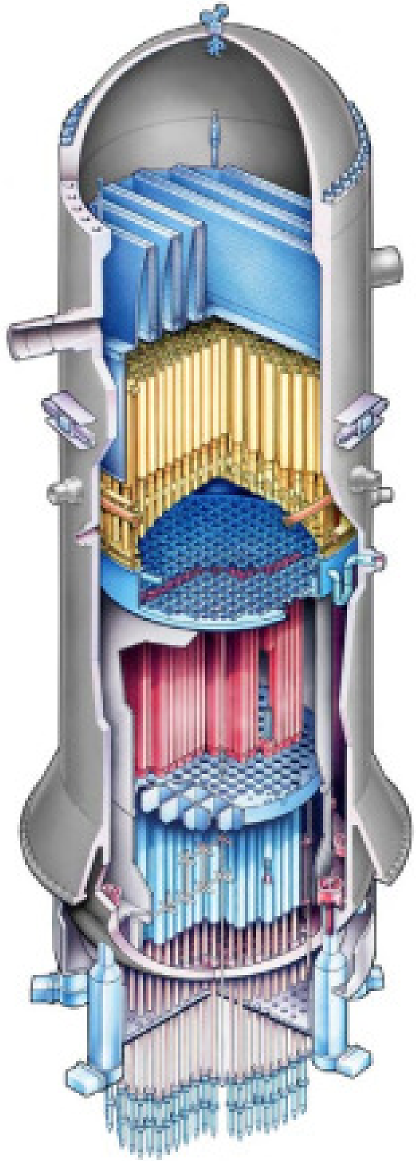
IAEA data, end of 2013. GWe = capacity in thousands of megawatts (gross)
Source: Nuclear Engineering International Handbook 2011, updated to 1/1/12
For reactors under construction: see paper Plans for New Reactors Worldwide.

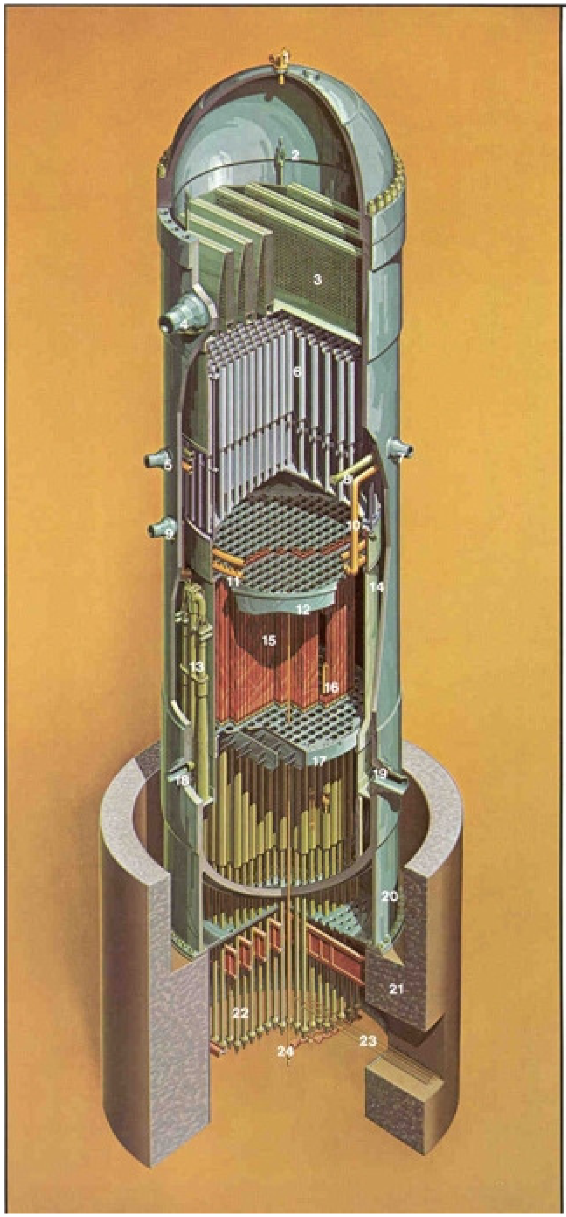


Reactor Type	Abbreviation	Operable	Shutdown	Under Construction
Pressurized Water Reactor	PWR	288	47	51
Boiling Water Reactor	BWR	78	37	4
Pressurized Heavy Water Reactor	PHWR	49	8	4
Light Water Graphite	LWGR	15	9	0
Gas Cooled Reactor	GCR	14	38	0
Fast Reactor	FBR	3	8	1
High Temperature Gas Cooled	HTGR	0	4	1
Heavy Water Gas Cooled	HWGCR	0	4	0
Heavy Water Light Water Reactor	HWLWR	0	2	0
Steam Generation Heavy Water	SGHWR	0	1	0
Other (Not Classified)	X	0	2	0
World Total		**447**	**160**	**61**

http://nuclearstreet.com/videos/dir/5-nuclear-reactor-pwr.html


Typical Boiling-Water Reactor



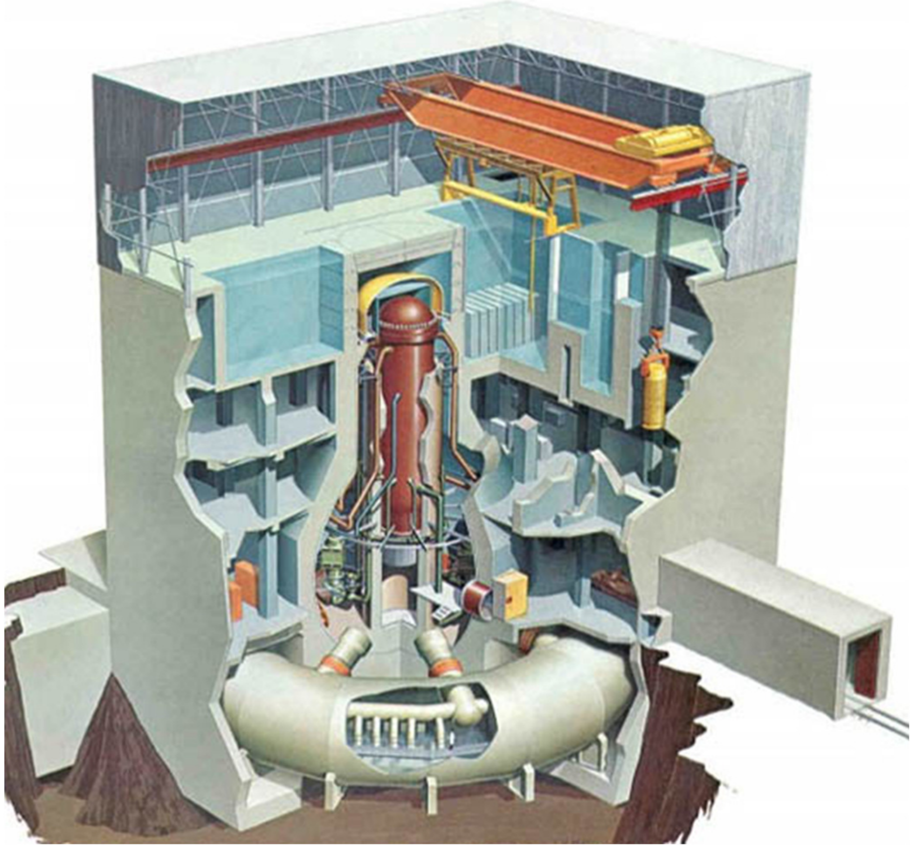


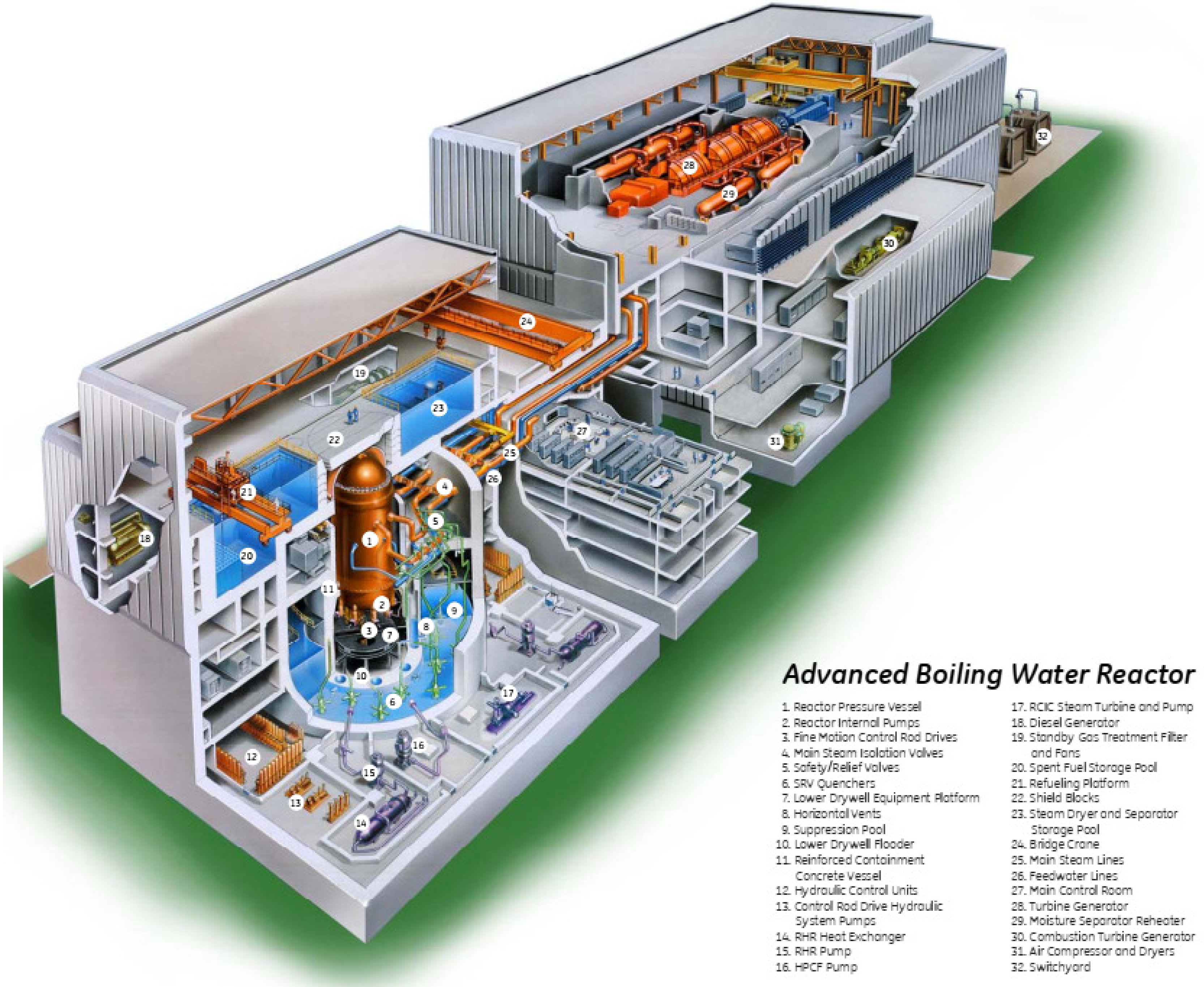
BWR/6

REACTOR ASSEMBLY

1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

GENERAL ELECTRIC





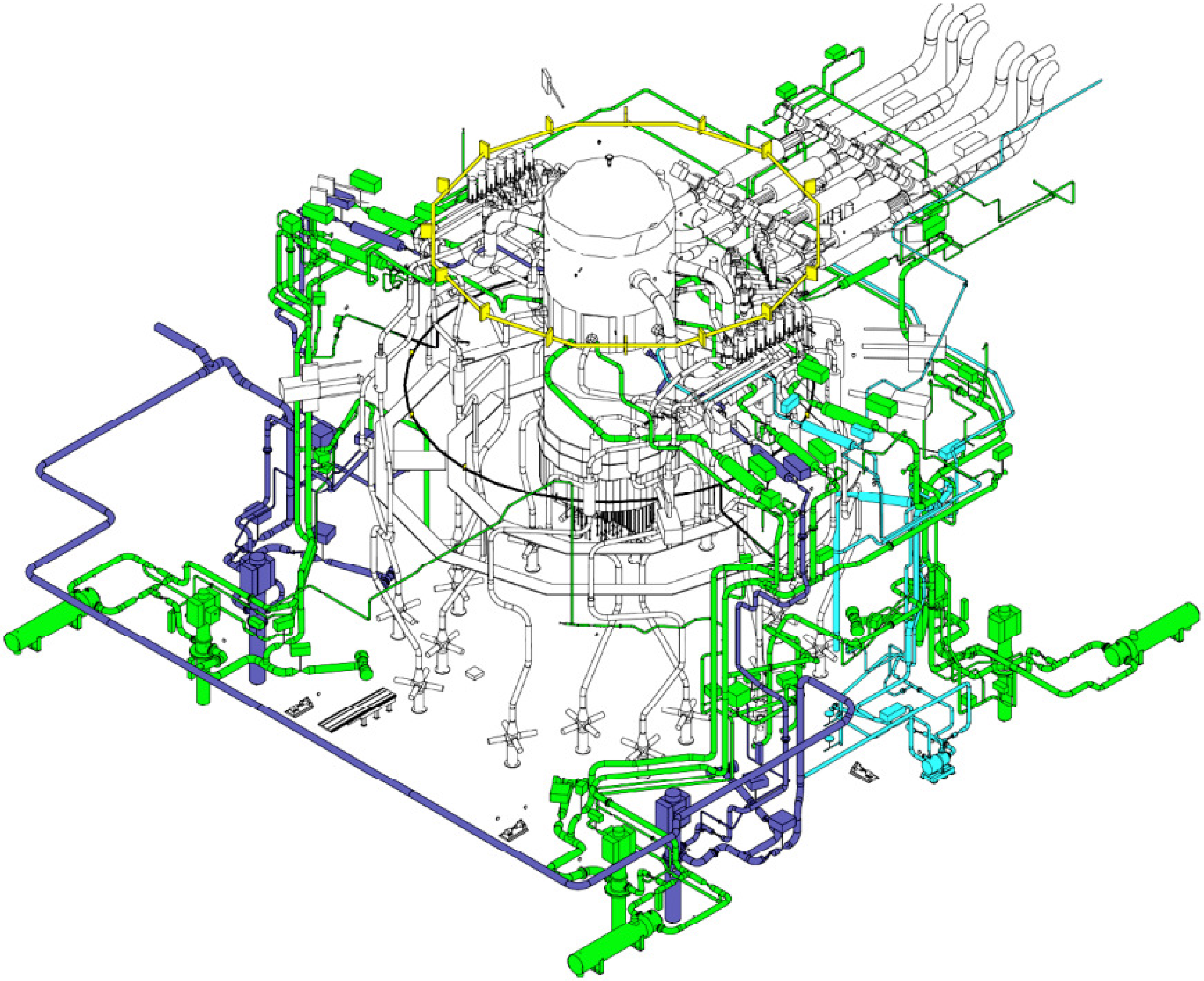
Advanced Boiling Water Reactor

1. Reactor Pressure Vessel
2. Reactor Internal Pumps
3. Fine Motion Control Rod Drives
4. Main Steam Isolation Valves
5. Safety/Relief Valves
6. SRV Quenchers
7. Lower Drywell Equipment Platform
8. Horizontal Vents
9. Suppression Pool
10. Lower Drywell Flooder
11. Reinforced Containment Concrete Vessel
12. Hydraulic Control Units
13. Control Rod Drive Hydraulic System Pumps
14. RHR Heat Exchanger
15. RHR Pump
16. HPCF Pump
17. RCIC Steam Turbine and Pump
18. Diesel Generator
19. Standby Gas Treatment Filter and Fans
20. Spent Fuel Storage Pool
21. Refueling Platform
22. Shield Blocks
23. Steam Dryer and Separator Storage Pool
24. Bridge Crane
25. Main Steam Lines
26. Feedwater Lines
27. Main Control Room
28. Turbine Generator
29. Moisture Separator Reheater
30. Combustion Turbine Generator
31. Air Compressor and Dryers
32. Switchyard

Reactor Core Isolation Cooling (RCIC)

HIGH PRESSURE CORE FLOODER (HPCF)

Residual Heat Removal (RHR)

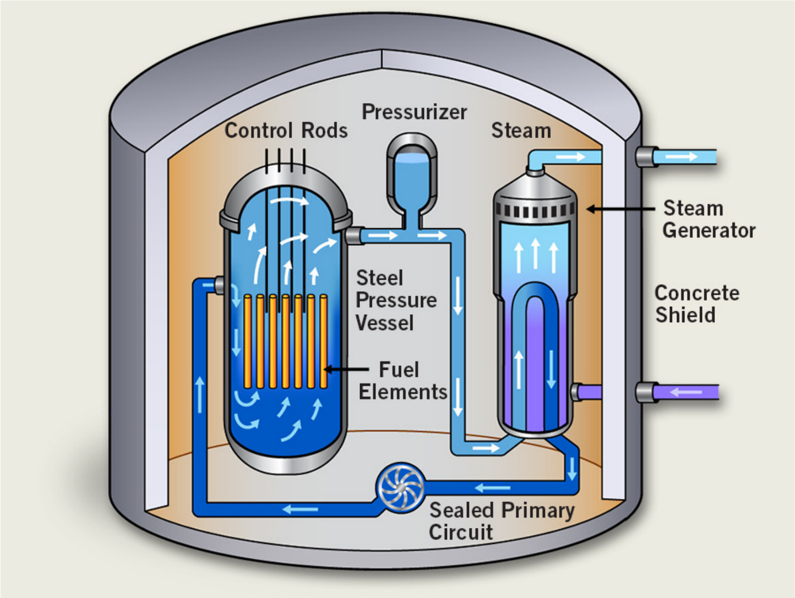


🟩 RHR

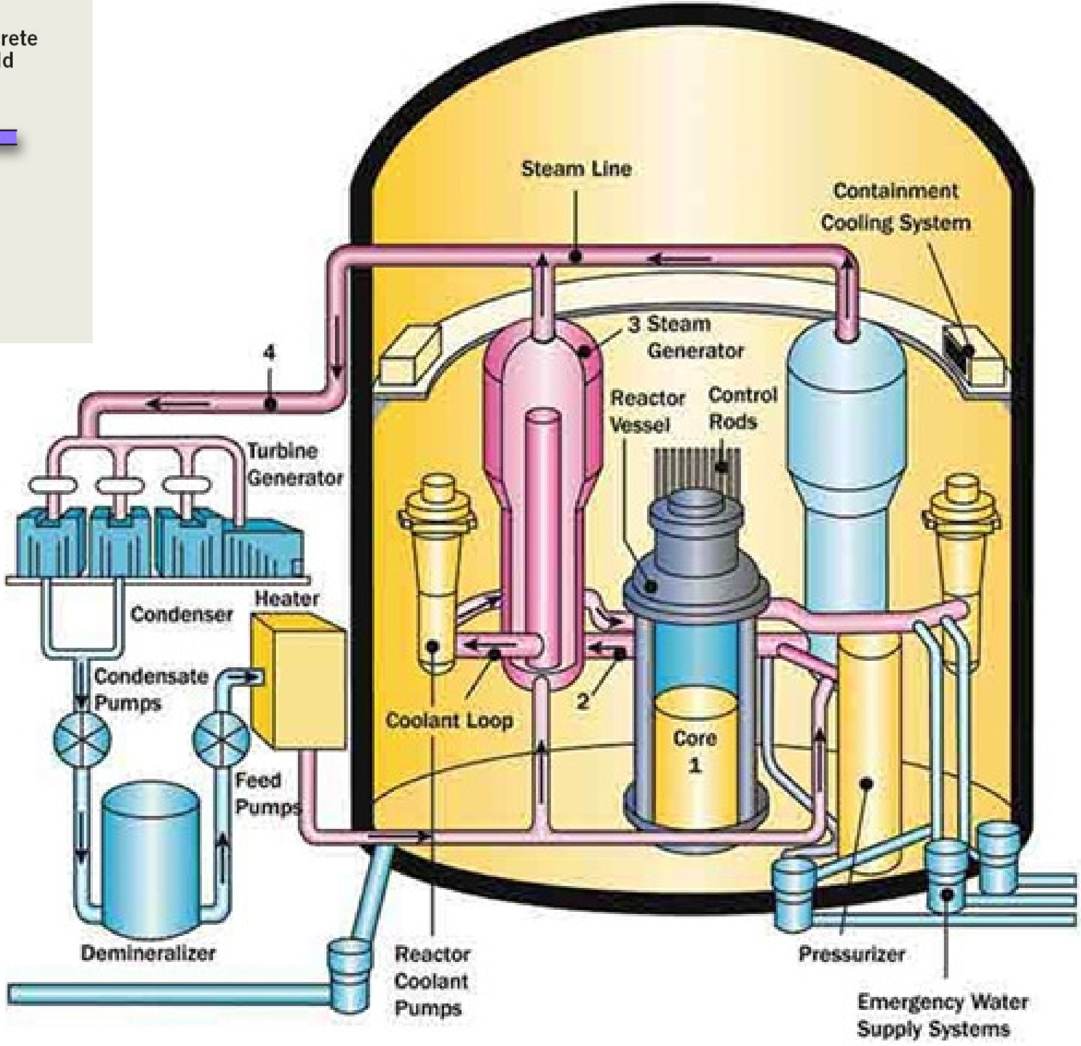
🟦 HPCF

🟦 RCIC

🟨 Containment Spray

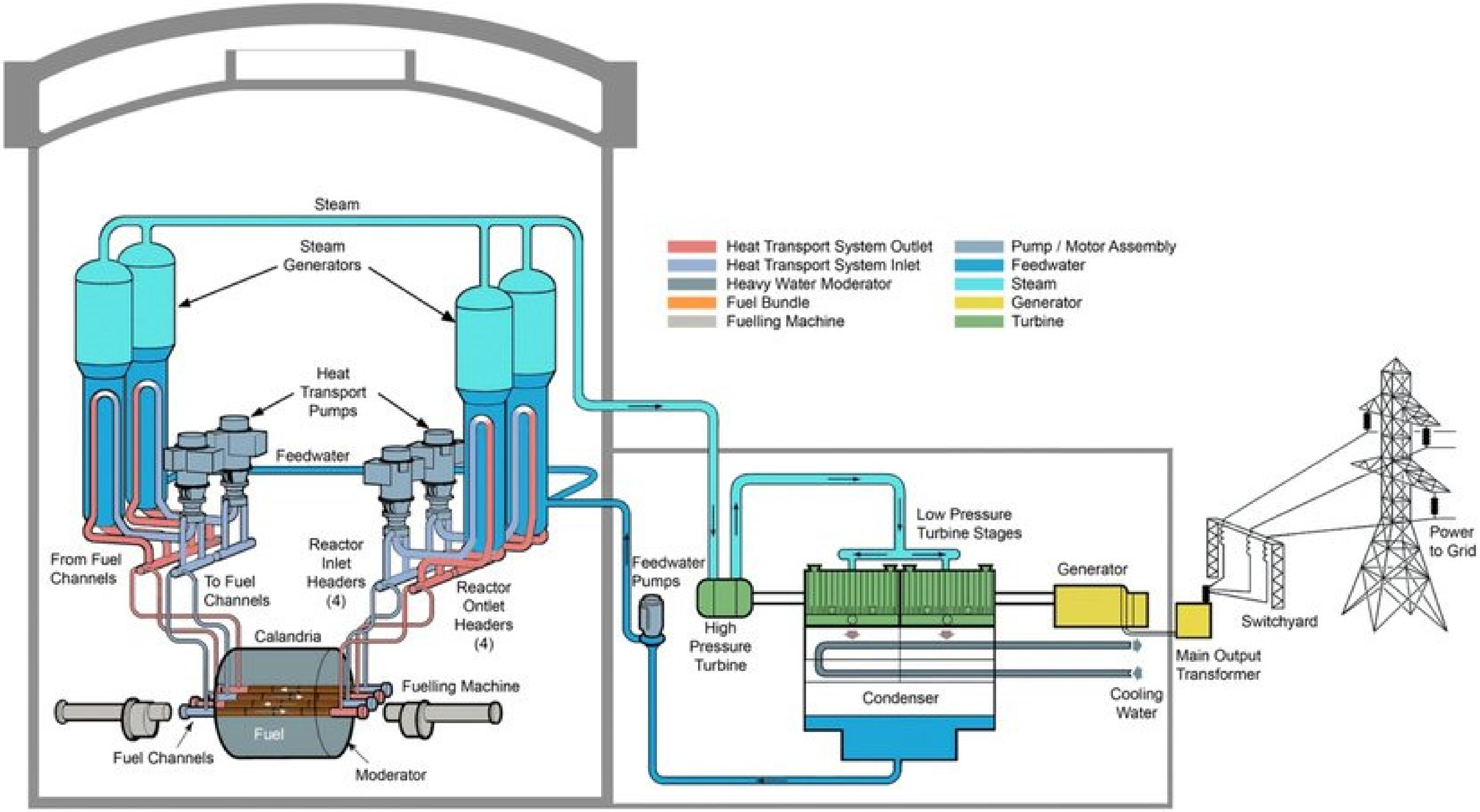


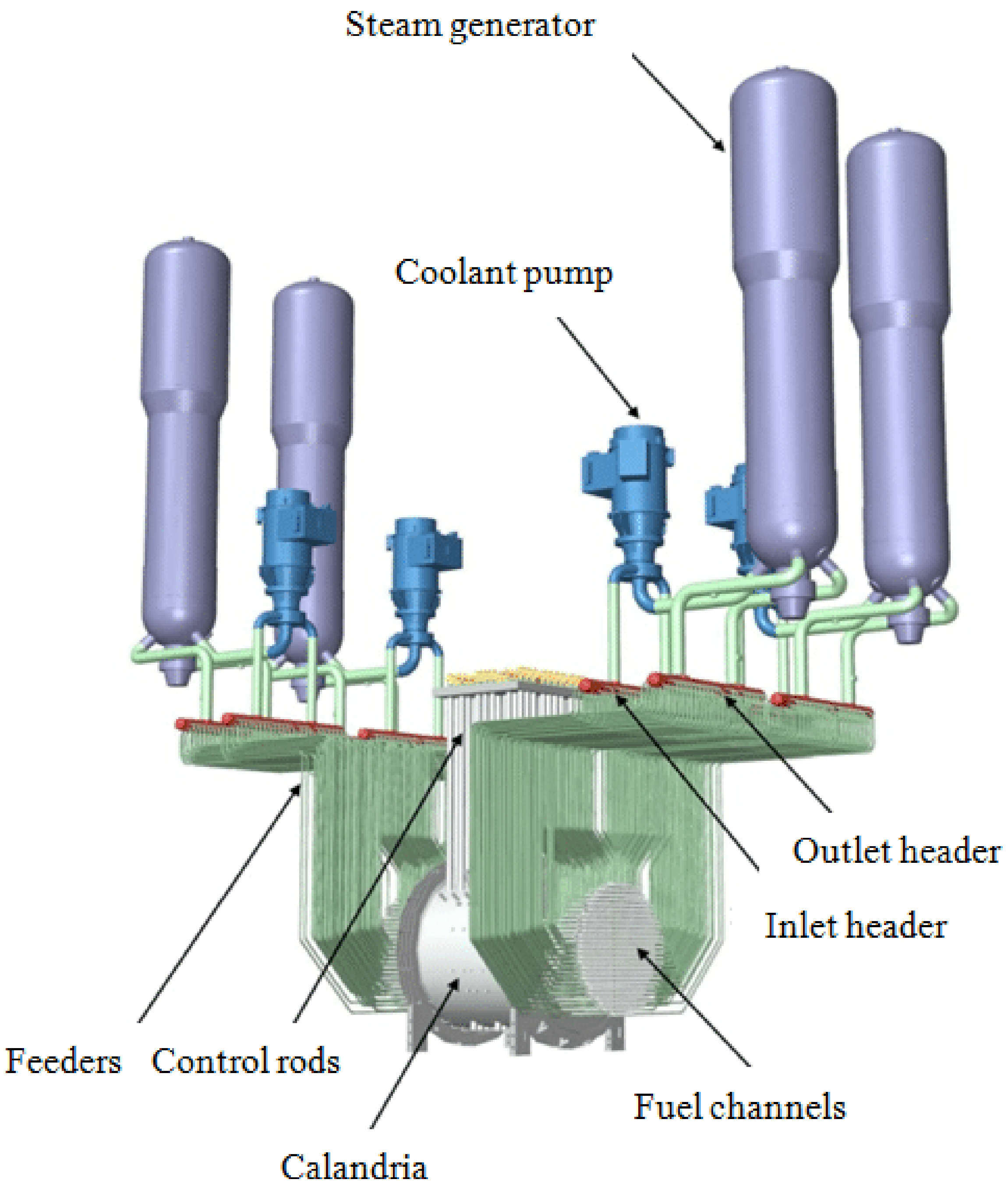
Typical Pressurized-Water Reactor



http://nuclearstreet.com/videos/dir/5-nuclear-reactor-pwr.html

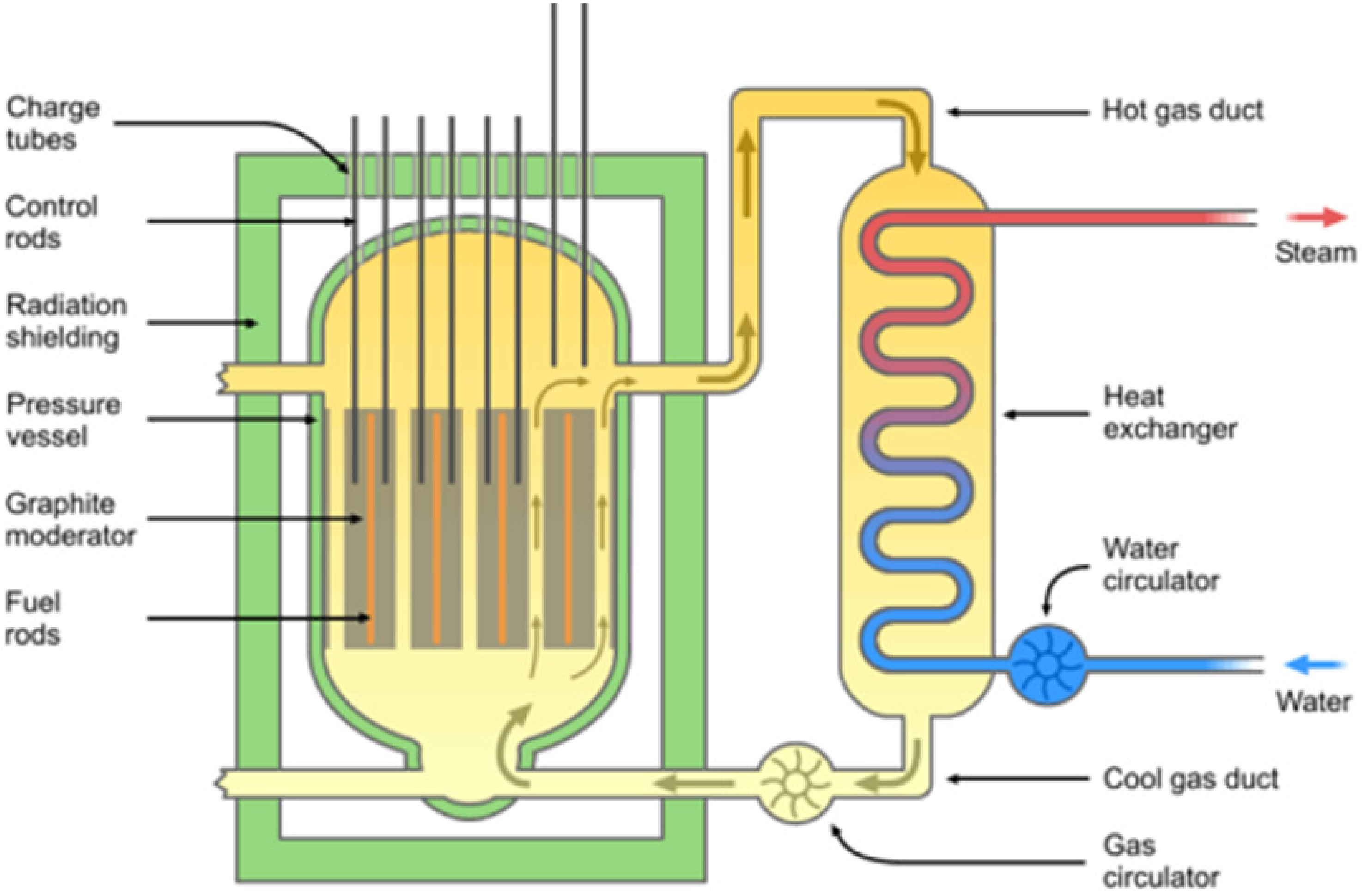
CANDU reactor is a type of nuclear reactor which was developed in Canada (1950), and is currently used in nuclear power plants for electrical generation in various countries around the world. CANDU stands for CANada Deuterium Uranium (CANDU), which reflects the key role of deuterium, or heavy water, which acts as the reactor's neutron moderator, a unique trait of the CANDU.[2] The reactors are also different from other reactors because they are designed to utilize natural uranium as a fuel (as opposed to enriched uranium)




Steam generator
Coolant pump
Outlet header
Inlet header
Feeders
Control rods
Fuel channels
Calandria

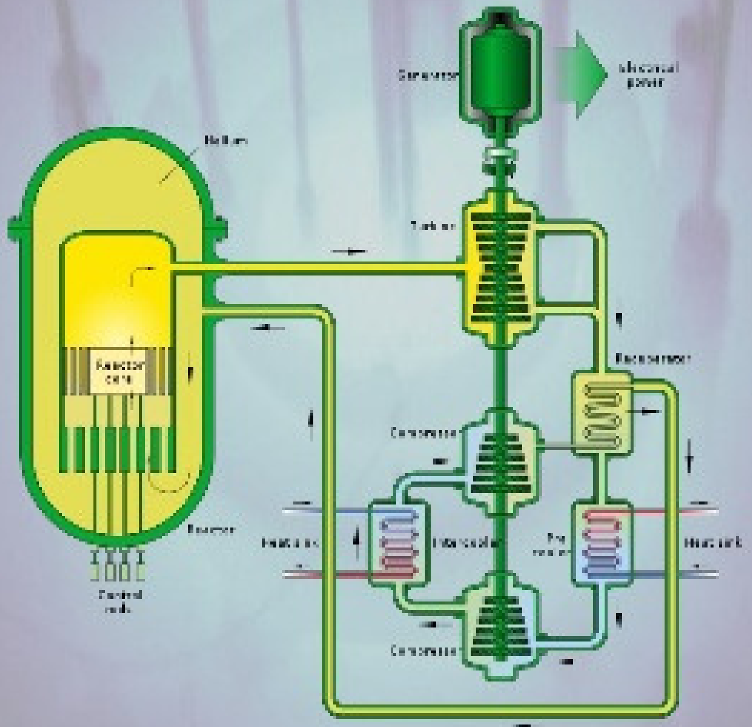
Gas Cooled Reactor

GCR can operate at temperatures up to 800–850°C and yield an energy conversion efficiency exceeding 40% when using conventional steam turbine equipment or as high as 50% when using more advanced gas turbine equipment.



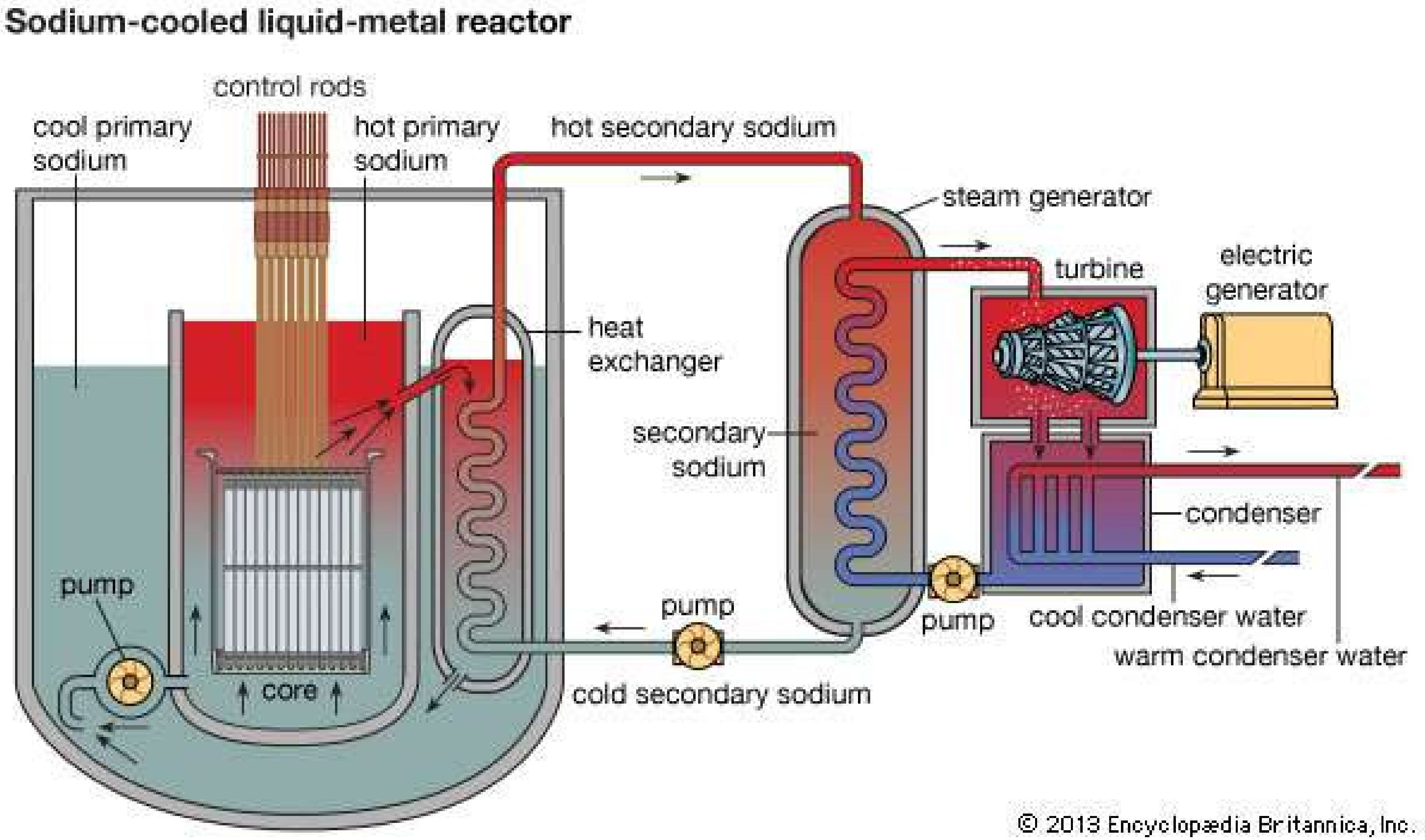
Gas-cooled Fast Reactor

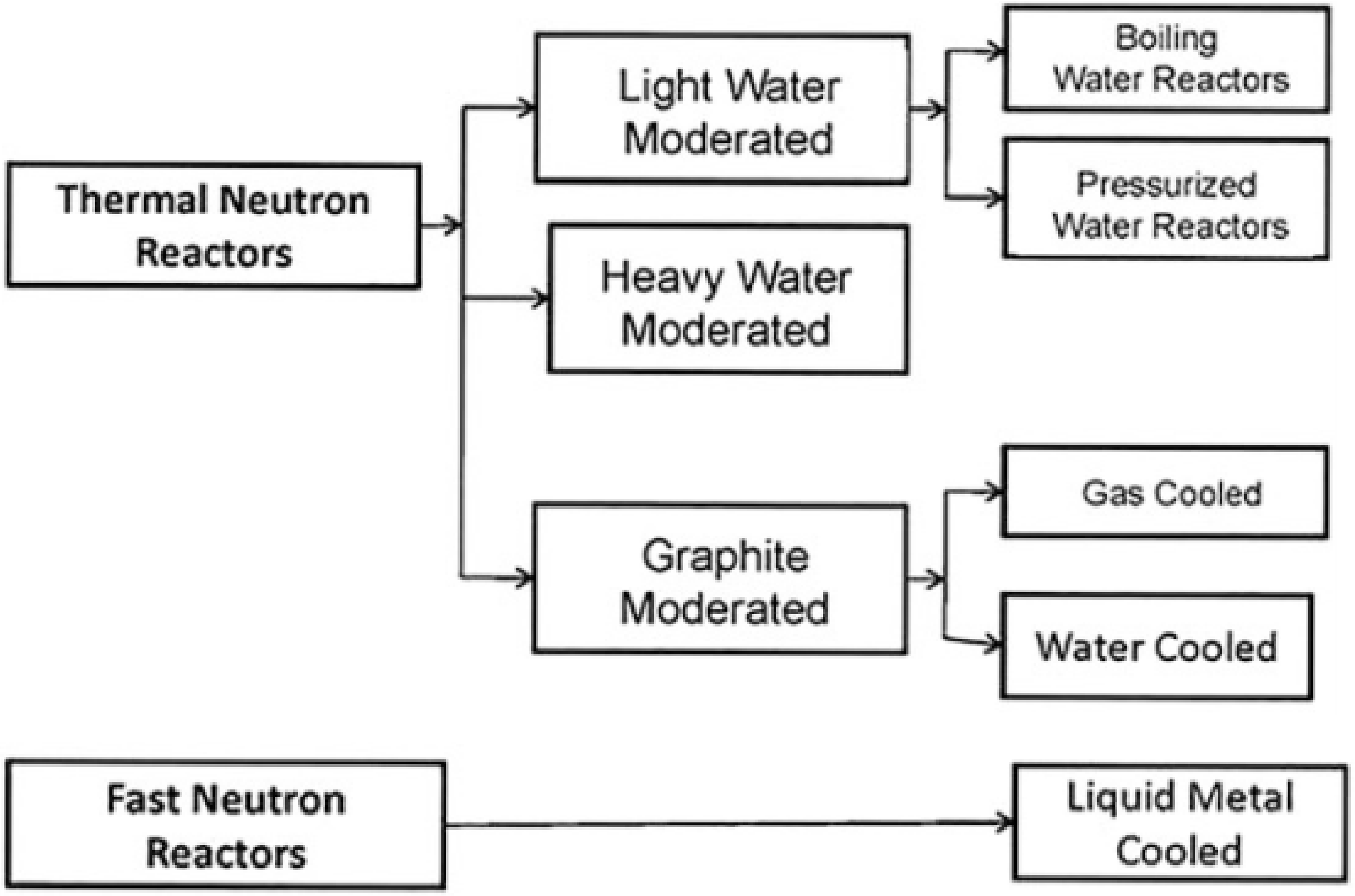
- GFR
  - CO_2 or He
  - Higher Temperature
  - Non activated coolant
  - No flashes to steam
  - Have to consider:
    - Neutron absorption leads to positive void coefficient
- Fuel Elements
  - Ceramics
  - Good at High Temperature
  - Retain Fission Fragments



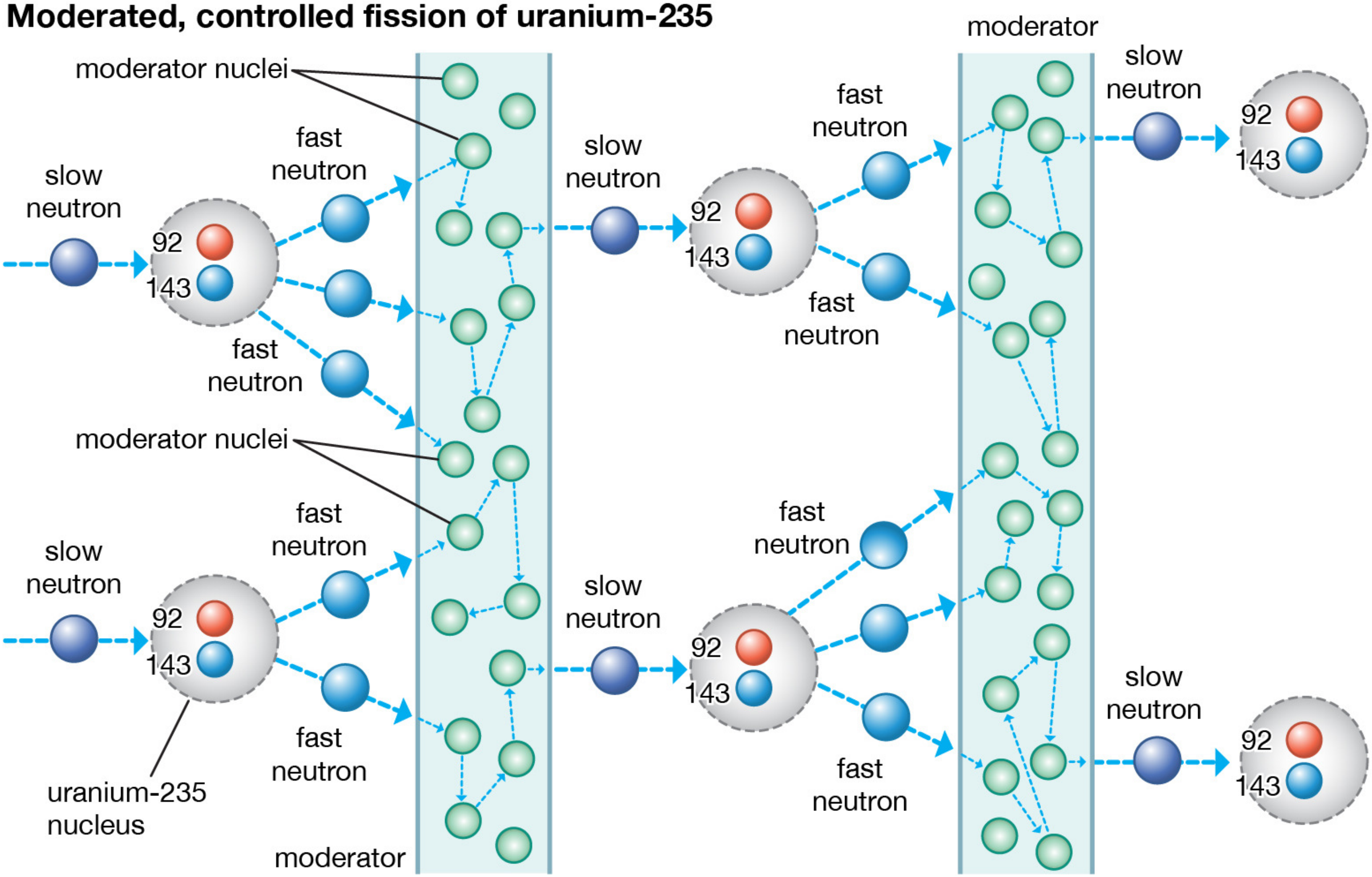
Fast Neutron Reactor (FNR)

FBRs can utilize uranium at least 60 times more efficiently than a normal reactor




Thermal Neutron Reactors
Light Water Moderated
Boiling Water Reactors
Pressurized Water Reactors
Heavy Water Moderated
Graphite Moderated
Gas Cooled
Water Cooled
Fast Neutron Reactors
Liquid Metal Cooled

Moderated, controlled fission of uranium-235



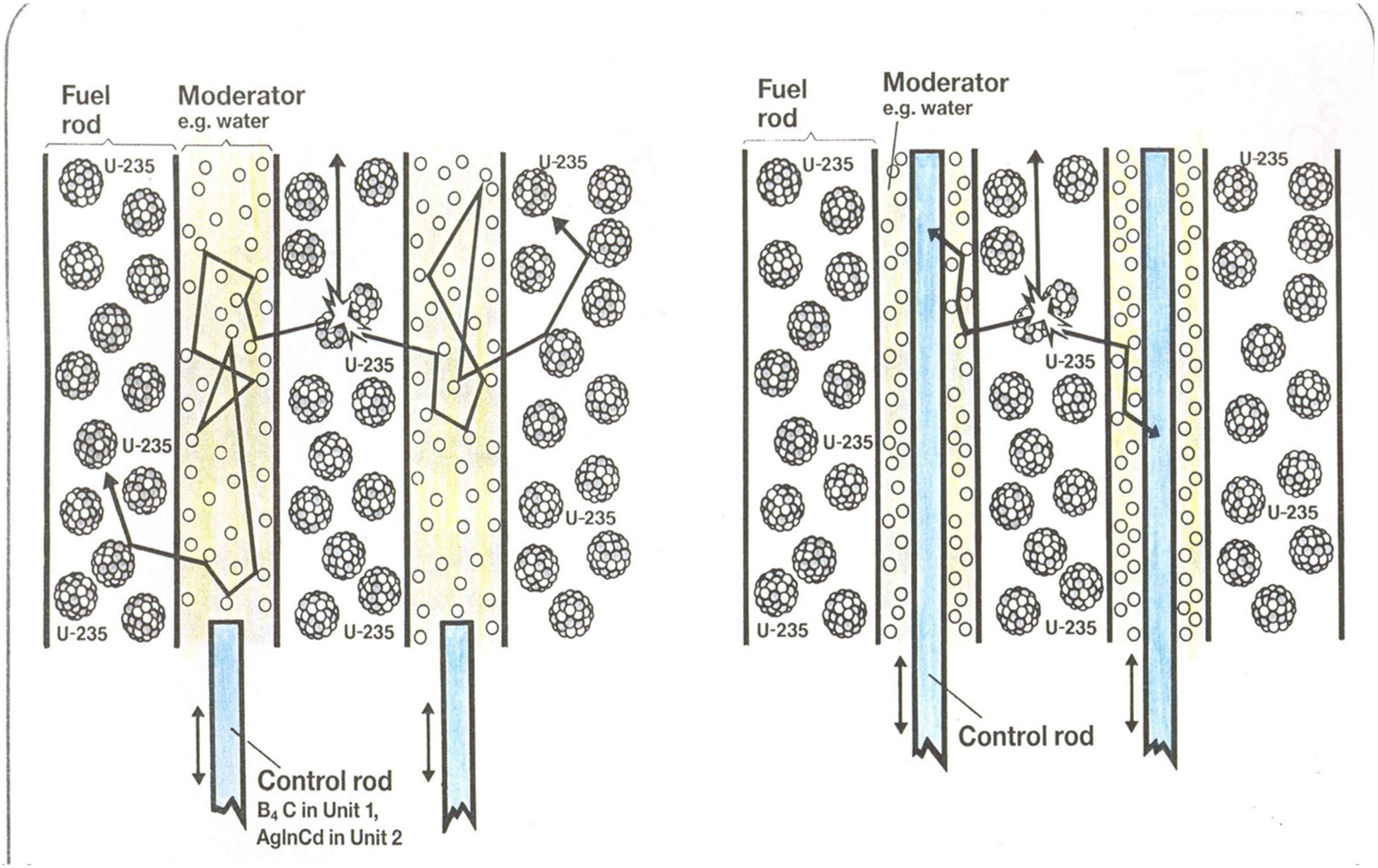

Fuel rod
Moderator
e.g. water
U-235
U-235
U-235
U-235
U-235
U-235
U-235
Control rod
B_4 C in Unit 1,
AgInCd in Unit 2
Fuel rod
Moderator
e.g. water
U-235
U-235
U-235
U-235
U-235
U-235
U-235
Control rod

Table 1.1 Some aspects of reactor types

Aspect	Reactor							
	Unit	PWR	BWR	RBMK	CANDU	AGR	HTR	LMFR
Characteristic of concepts								
Moderator		H_2O	H_2O	H_2O/C	D_2O	C	C	
Neutron spectrum		Thermal	Thermal	Thermal	Thermal	Thermal	Thermal	Fast
Fuel		UO_2 PuO_2	UO_2 PuO_2	UO_2 PuO_2	UO_2 PuO_2	UO_2	UO_2 PuO_2	UO_2 PuO_2
Type of fuel		Rods	Rods	Rods	Rods	Rods	Pebbles blocks	Rods
Coolant		H_2O	H_2O	H_2O	D_2O	CO_2	He	Na
Status of coolant		Liquid	Liquid/steam	Liquid/steam	Liquid	Gas	Gas	Liquid
Special aspects of fuel		Zircaloy canning	Zircaloy canning	Pressure tubes	Pressure tubes	Steel canning	Coated particles	Steel canning
Parameters of design								
Enrichment	%	3–4	3–4	2	<1.5	2	8	10
Fuel burnup (average)	MWd/kg	45	40	30	10	20	80	100
Core power density	MW/m^3	100	50	4	15	2	3	400
Coolant temperature	°C	290–325	200–285	200–285	200–305	250–650	250–750/950	380–540
Coolant pressure	MPa	16.0	~ 7.0	7.0	9.5	4.0	6.0	1.0
Steam pressure	MPa	6.5	7.0	7.0	4.3	18.0	18.0	17.0
Steam temperature	°C	280	285	285	250	530	530/600	500
Efficiency	%	33	33	32	30	40	40/45	40
Thermal power	MW	3800	3800	3000	1500	1500	200–600	750
Special aspects					Natural uranium		Gas turbine process heat	Breeding

PWR pressurized water reactor, *BWR* boiling water reactor, *RBMK* Russian boiling water reactor with graphite structures, *CANDU* Canadian heavy water reactor, *AGR* advanced gas-cooled reactor, *HTR* high-temperature reactor, *LMFR* liquid metal cooled fast reactor

1. *V*ery *h*igh-*t*emperature *r*eactor **(VHTR)**
2. *M*olten *s*alt *r*eactor **(MSR)**
3. *S*odium-cooled *f*ast *r*eactor **(SFR)**
4. *S*uper*c*ritical *w*ater-cooled *r*eactor **(SCWR)**
5. *G*as-cooled *fast reactor* **(GFR)**
6. *L*ead-cooled *f*ast *r*eactor **(LFR)**

outlet temperatures between 700 and 950 °C or more than 1000 °C in future.

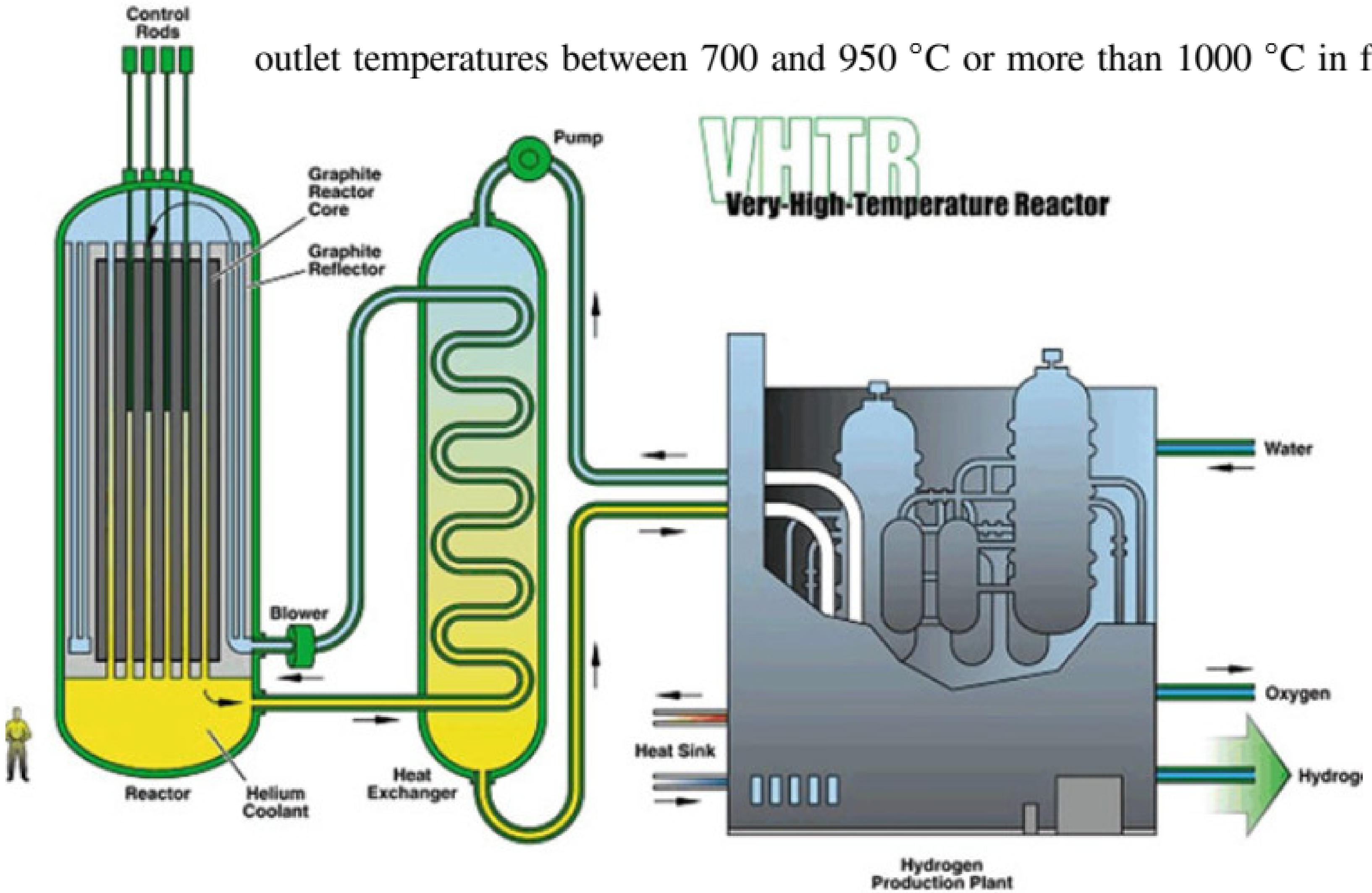


Fig. 18.22 Very high-temperature reactor. (Courtesy of the Generation IV International Forum)

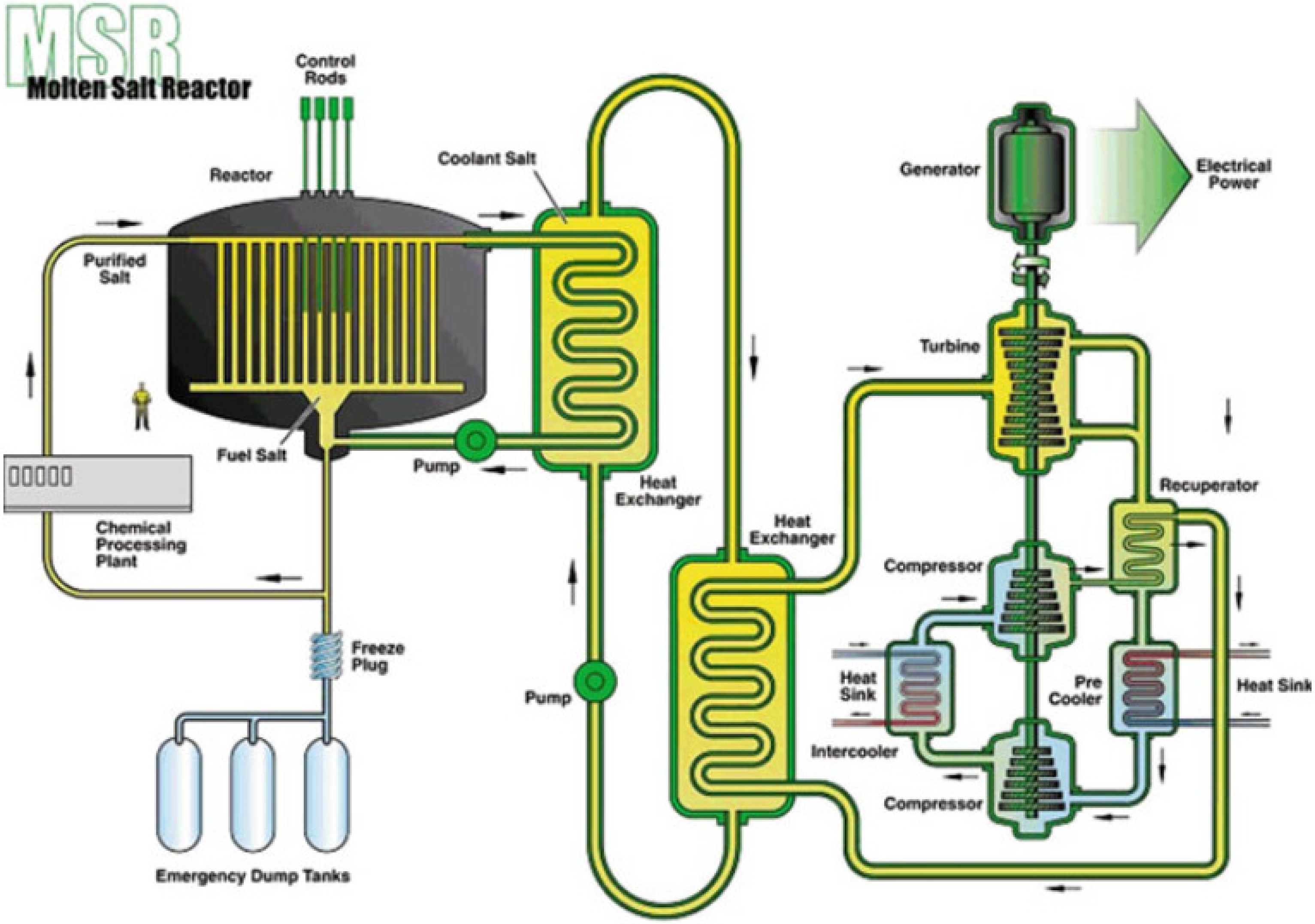


Fig. 18.23 Molten salt reactor. (Courtesy of the Generation IV International Forum)

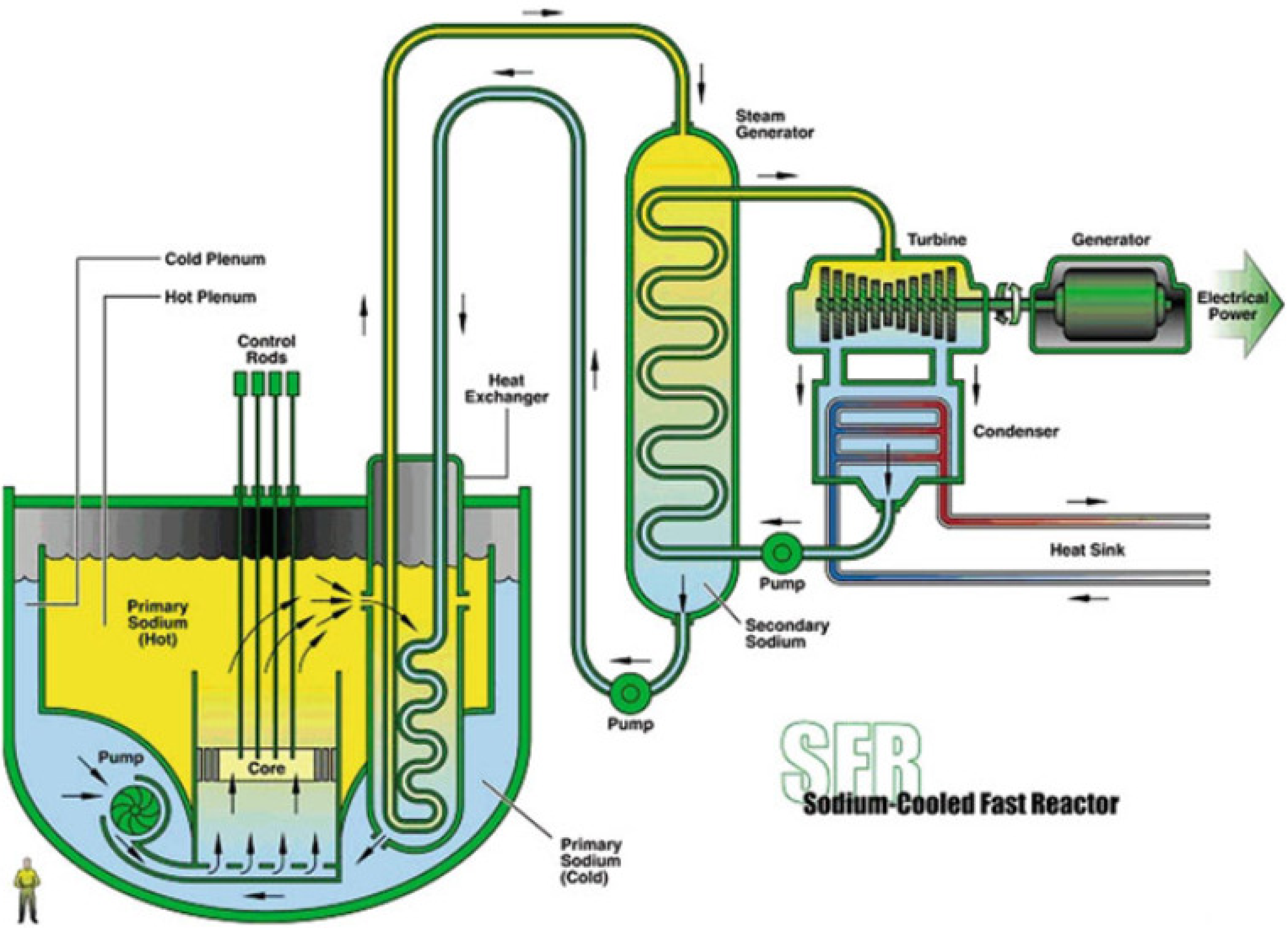


Fig. 18.24 Sodium-cooled fast reactor. (Courtesy of the Generation IV International Forum)

The supercritical water-cooled reactors (SCWRs) are high-temperature, high-pressure, light water-cooled reactors that operate above the thermodynamic critical point of water (374 °C, 22.1 MPa).

The efficiency of a SCWR can approach 44% or more, compared to 34–36% for current reactors.

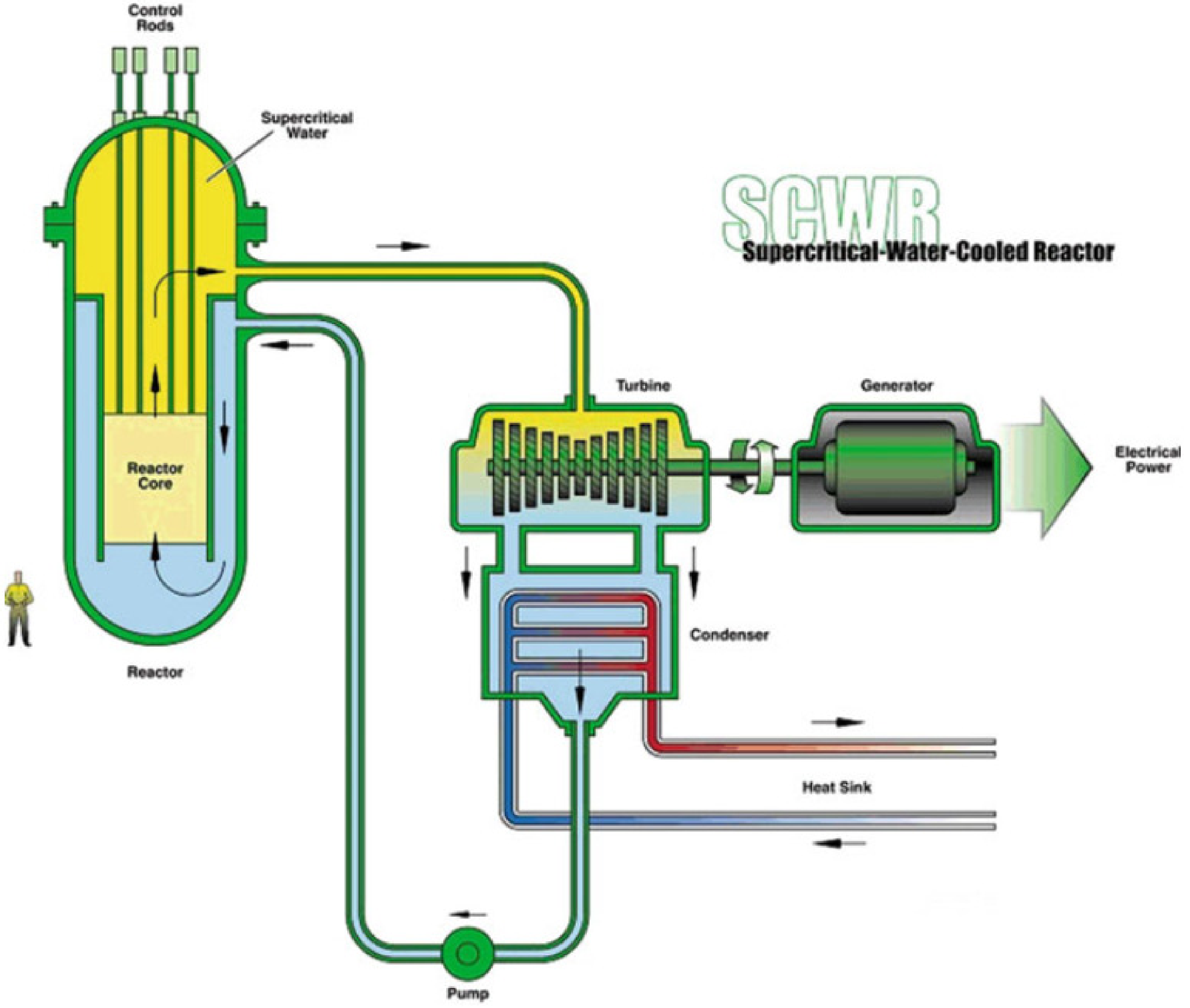


Fig. 18.25 Supercritical water-cooled reactor. (Courtesy of the Generation IV International Forum)

Gas-Cooled Fast Reactor (GFR)

The reference design for GFR is based around a 2400 MWth reactor core
The coolant is helium and the core outlet temperature will be of the order of 850 °C.

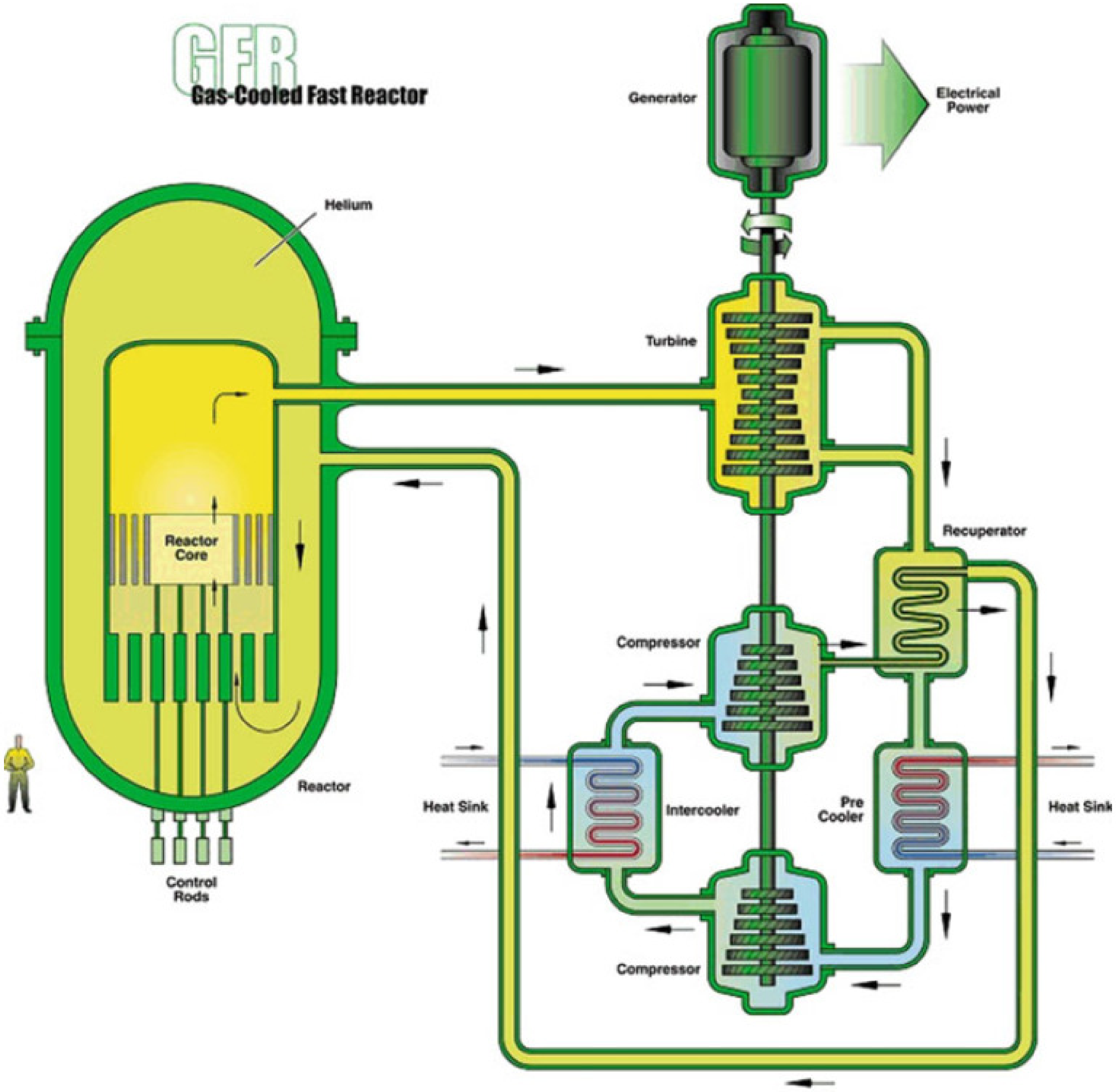


Fig. 18.26 Gas-cooled fast reactor. (Courtesy of the Generation IV International Forum)

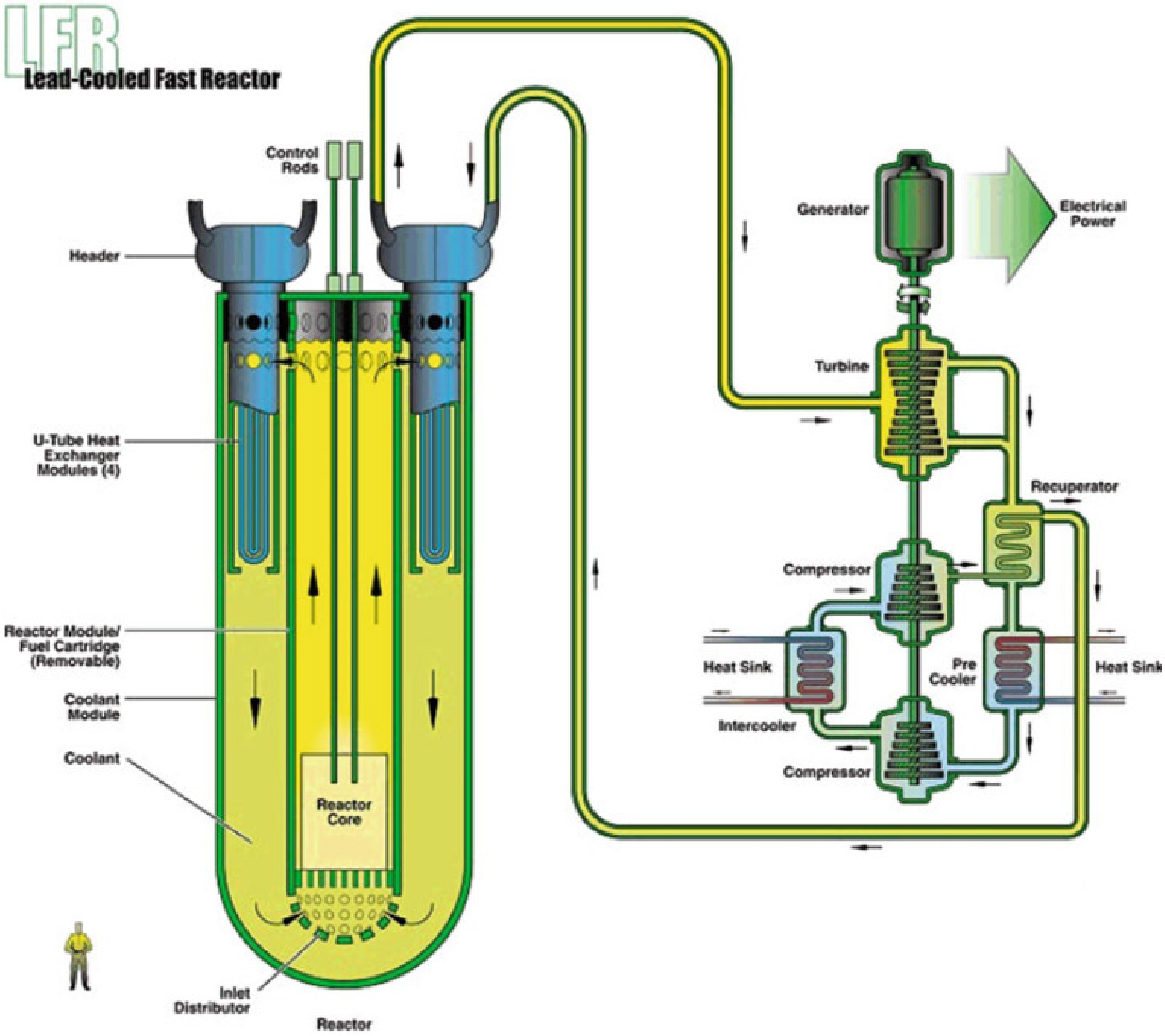


Fig. 18.28 Lead-cooled fast reactor. (Courtesy of the Generation IV International Forum)

Table 18.1 Summary of the main characteristics of the six Generation IV systems

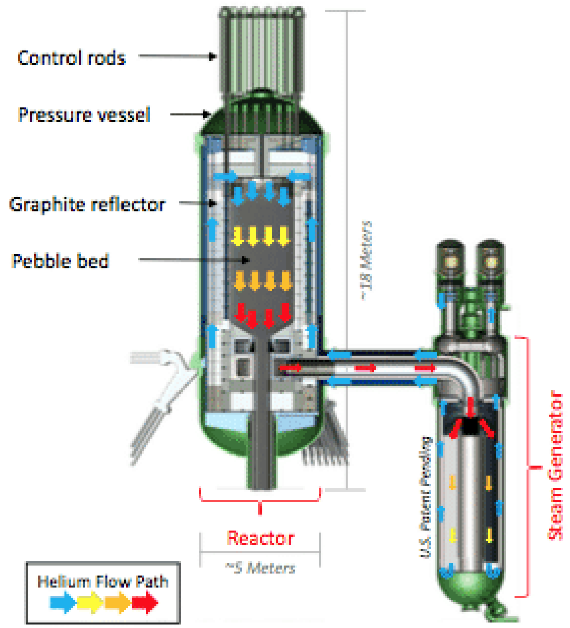
System	Neutron spectrum	Coolant	Temp. ^{0}C	Fuel cycle	Size (MWe)
VHTR (very high-temperature gas reactor)	Thermal	Helium	900 to 1000	Open	250–300
SFR (sodium-cooled fast reactor)	Fast	Sodium	550	Closed	30–150, 300–1500 1000–2000
SCWR (supercritical water-cooled reactor)	Thermal/fast	Water	510–625	Open/ closed	300–700 1000–2000
GFR (gas-cooled fast reactor)	Fast	Helium	850	Closed	1200
LFR (lead-cooled fast reactor)	Fast	Lead	480–800	Closed	20–180 300–1200 600–1000
MSR (molten salt reactor)	Epithermal	Fluoride salt	700–800	Closed	1000

Characteristics of HTR

- thermal spectrum
- helium as coolant
- graphite as structural material and moderator
- coated particle fuel (TRISO)
- high burnup of fuel
- high helium outlet temperature
- fuel element form (hexagonal, spherical)
- safety characteristics: self acting decay heat removal with limitation of maximal temperature during accidents
- different applications (steam turbine, gas turbine, combined cycles, high temperature process heat)

TRISO particle – 1 mm diameter

The Xe-100 Reactor Cannot Melt Down



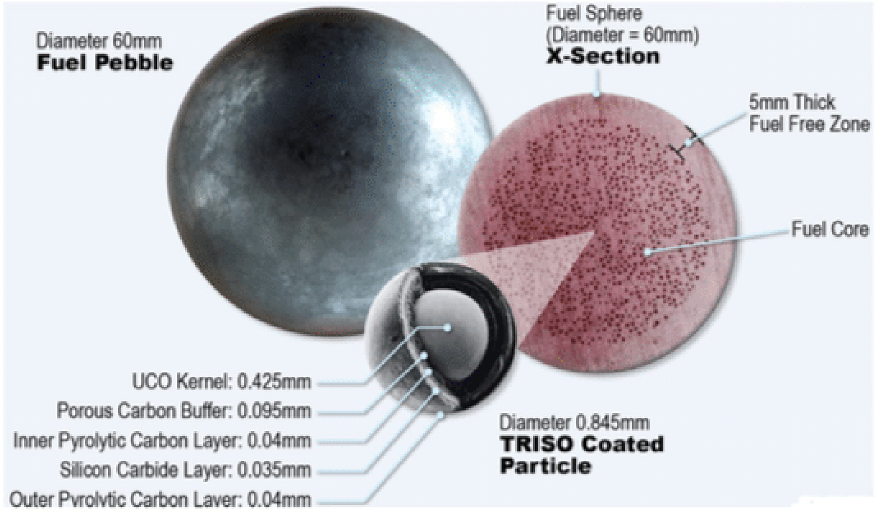
Xe-100 Reactor Benefits

- Helium transports heat from the reactor to the steam generator; no cooling fluid required
- Reactor core design eliminates the possibility of meltdown
- On-line refueling allows for continuous operations
- Able to quickly respond to energy demands
- Used fuel is proliferation resistant

حتی در مواردی که جریان خنک کننده متوقف می شود و فشار سیال خنک کننده برابر صفر شود (فشار gage) ، سیستم راکتور نمی تواند بیش از حد گرم شود زیرا انتقال حرارت کافی از طریق هدایت به محیط اطراف وجود دارد تا گرمترین مکان ها در داخل راکتور زیر ۱۶۰۰ درجه سانتیگراد باشد. سوخت TRISOبرای آزمایش نشان داده شده است که NGNP می تواند یکپارچگی خود را حفظ کند حتی اگر در مدت زمان طولانی تا ۱۸۰۰ درجه سانتیگراد گرم شود.

Next Generation Reactor Program (NGNP)

Fuel is the Key to Unsurpassed Safety



هر راکتور حاوی حدود ۱۷۰،۰۰۰ گوی کروی است. قطر کره ها ۶۰ میلی متر و لایه گرافیت با ضخامت ۵ میلی متر در قسمت خارجی آن است. در داخل این کره ها، ترکیبی از حدود ۲۵۰۰۰ ذره کوچک با یک چسب گرافیت وجود دارد. قطر ذرات کمتر از یک میلی متر است. قطر هسته سوخت در مرکز ذرات حدود ۴۷۵ میکرون است. با چهار لایه احاطه شده است. یک لایه متخلخل از گرافیت پیرولیتی ، یک لایه متراکم از گرافیت پیرولیتی ، یک لایه از کاربید سیلیکون و یک لایه نهایی از گرافیت پیرولیتی متراکم.