Nuclear Energy

Some Basics & Statistics

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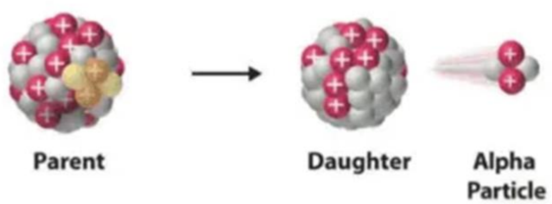
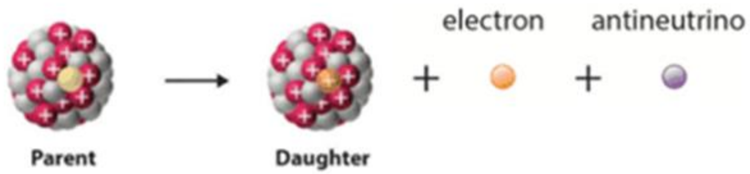
DE LA RECHERCHE À L'INDUSTRIE

Nuclear reactions

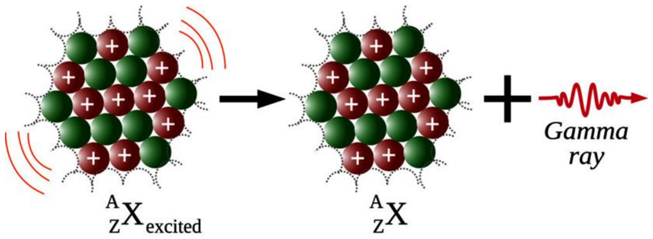
Spontaneous and induced reactions

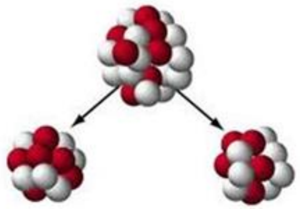


$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He $$



$$ {}^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + \beta^{-} + \bar{\nu_e} $$

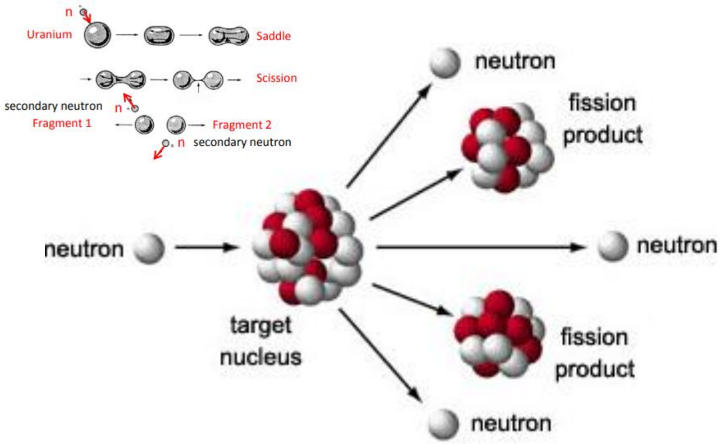




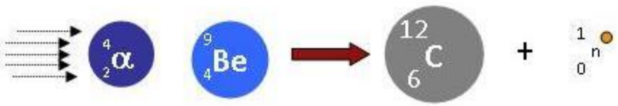
Spontaneous fission :

- Occurs with a very heavy nucleus (Z>90)
- The electromagnetic repellent force overcomes the strong nuclear force
- The nucleus splits
- Will eject 2-4 neutrons per reaction

Induced fission



≈ 200 MeV



$$ a + A \Rightarrow B + b $$

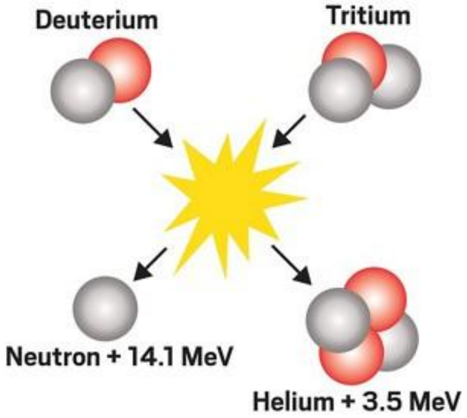
Incident particle

Nucleus target

Residual nucleus

Ejected particle

Induced fusion



Nuclear reactions

$$a + A \Rightarrow B + b$$

Incident particle

Nucleus target

Residual nucleus

Ejected particle

Some nuclear reactions release energy while other reactions require input energy to occur

The amount of energy released or absorbed in a nuclear reaction (in the center of mass reference frame) is called the Q value or Reaction Energy

$$Q = [(M_a + M_A - (M_b+M_B)] c^2$$

If $Q > 0 \Leftrightarrow$ Exoergic reaction

If $Q<O \Leftrightarrow$ Endoergic reaction

An endoergic reaction could not proceed unless the incoming particle provides the reaction energy Q (in CM).

Exoenergetic Nuclear Reactions

- Fusion

Deuterium + Tritium ⇨ Helium + Neutron

	^{2}H +	^{3}H ⇨	^{4}He +	^{1}n
E_L/A(MeV)	1,11	2,83	7,07	0
E_L (MeV)	2,22	8,5	28,28	

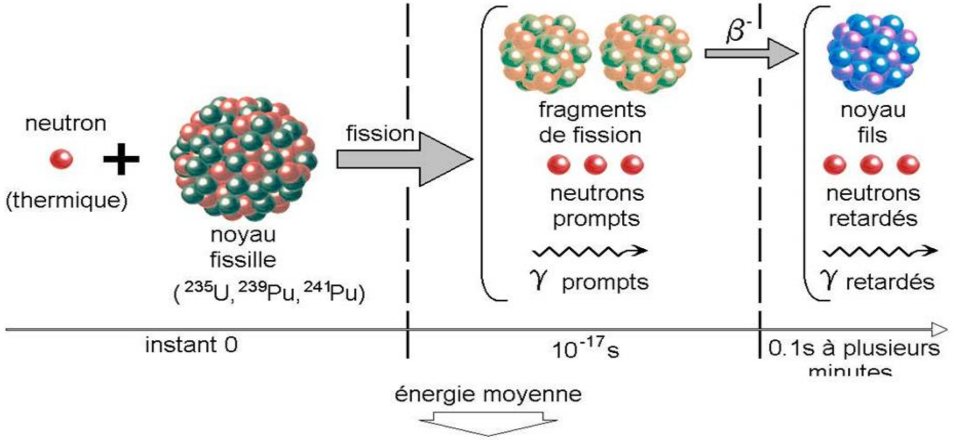
17,6 MeV generated (3.5 MeV/nucl.)

- Fission

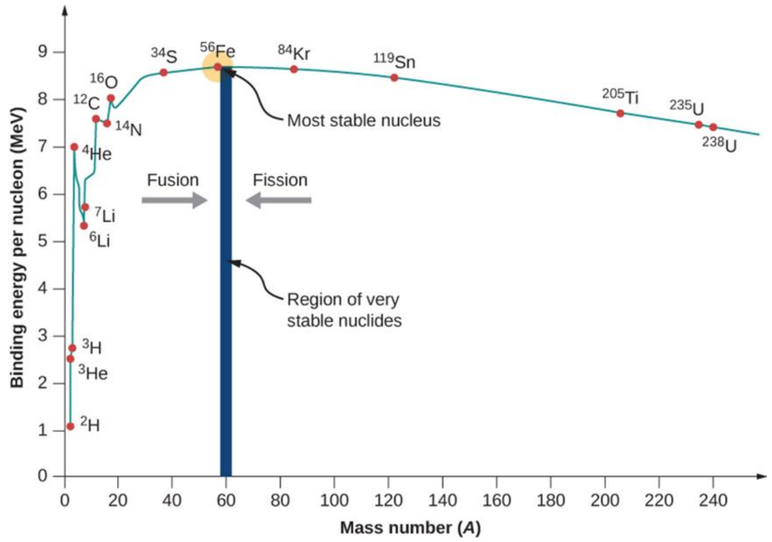
Neutron + Uranium fissile ⇨ Fragments de fission + Neutrons

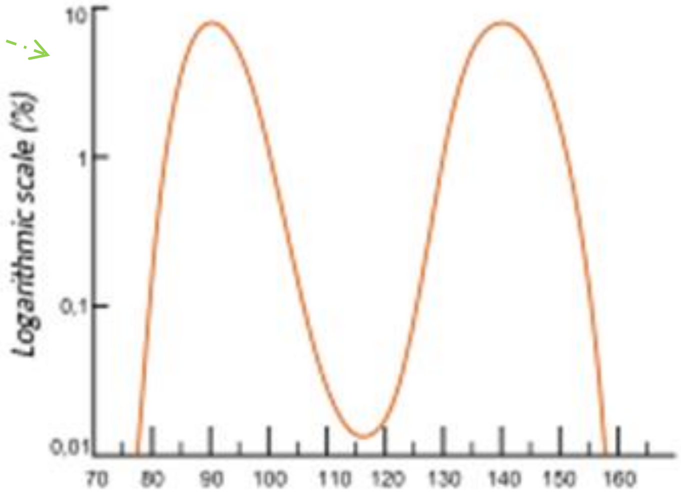
	^{1}n +	^{235}U ⇨	^{95}Zr +	^{138}Te +	3 ^{1}n
E_L/A(MeV)	0	7,5	8,6	8,3	0
E_L (MeV)		1760	800	1150	

200 MeV generated (0.8 MeV/nucl.)



- neutrons prompts :	2 MeV	2 à 3 par fission
- neutrons retardés :	500 KeV	0,6 10^{-2} à 1,6 10^{-2} par fission
- γ retardés :	1 MeV	5 à 7 par fission

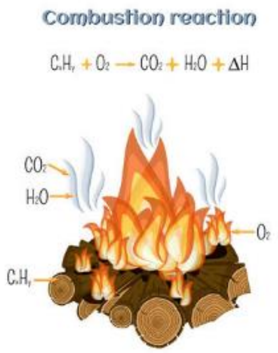




Distribution of Uranium-235 fission products (A)

Conventional combustion

- Chemical reaction of H or C with O :
  - $H_2 + 0{,}5\ O_2 \Rightarrow H_2O$ with
    E = 1,4 eV/atom of H
  - $C + O_2 \Rightarrow CO_2$
    E = 4 eV/atom

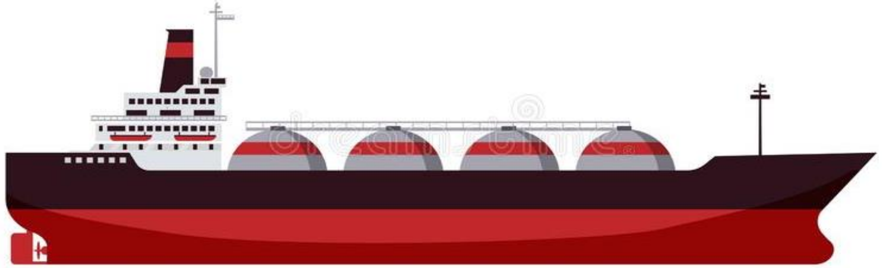


- Energy balance 10^7 à 10^8 **<u>lower</u>** than nuclear reactions :
  - Fission (**200 MeV/reaction**, 0,8 MeV/nucleon)
  - Fusion (**17,6 MeV/reaction**, 3,5 MeV/nucleon)

To produce 1 GWE ≡ 1.25 % of the French electricity consumption (523 TWh in 2021)

1 year of production with availability rate of 75%

Gas ⇒ 1.8 billions m^3

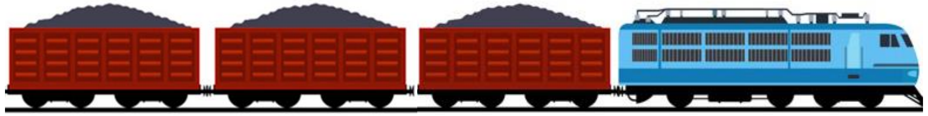


30 LNG* Tankers

Oil ⇒ 1 300 000 tons

15 to 45 Oil Tankers

Coal ⇒ 2 000 000 tons



600 Trains

Uranium ⇒ 150 t of Nat. U

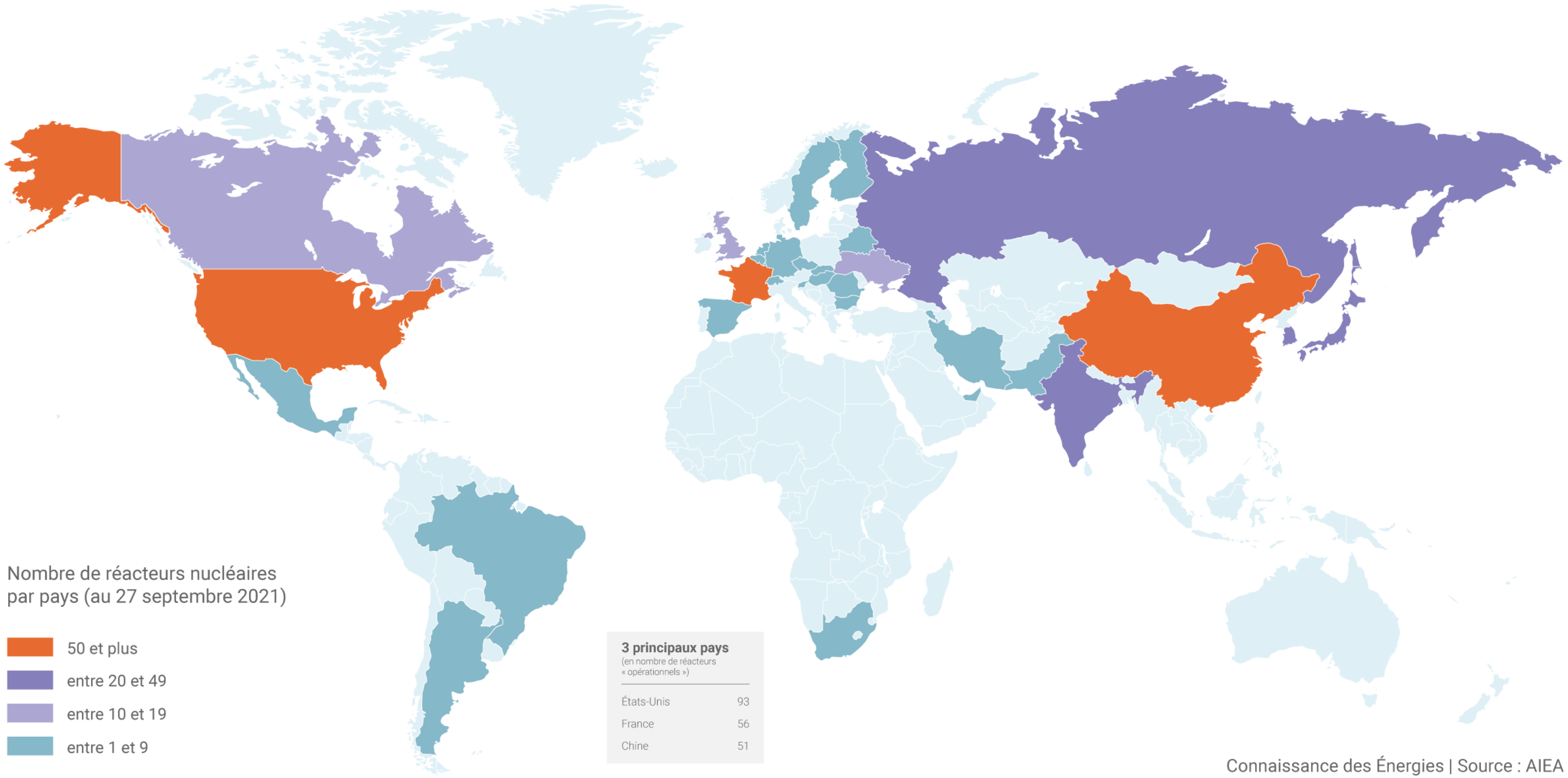
(25 t of 4% enriched Uranium

6 Semi-Trailer Trucks

(*)Liquid Natural Gas

Worldwide electronuclear landscape: 442 reactors in the world

Monde Nombre de réacteurs nucléaires « opérationnels » selon l'AIEA



Nuclear Power Status 2022

Reactors in operation**

393.8 GW(e) total net capacity

438 reactors

Reactors under construction

59.3 GW(e) total net capacity

58 reactors

Operating experience

19 764 reactor-years of operation (cumulative)

Nuclear power data and statistics

IAEA

Power Reactor Information System

PRIS

Nuclear power: electricity and beyond

CO₂ avoided **1.25** Gt

Electricity produced **2 486.8** TWh

Non-electric applications

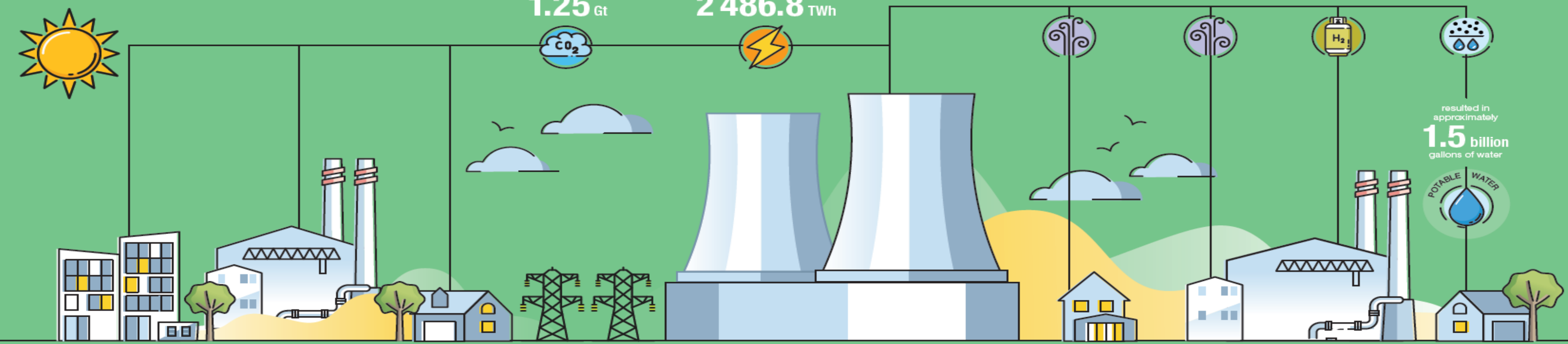
District heating **1 418** GWh electrical equivalent of heat

Industrial heating **1 341** GWh electrical equivalent of heat

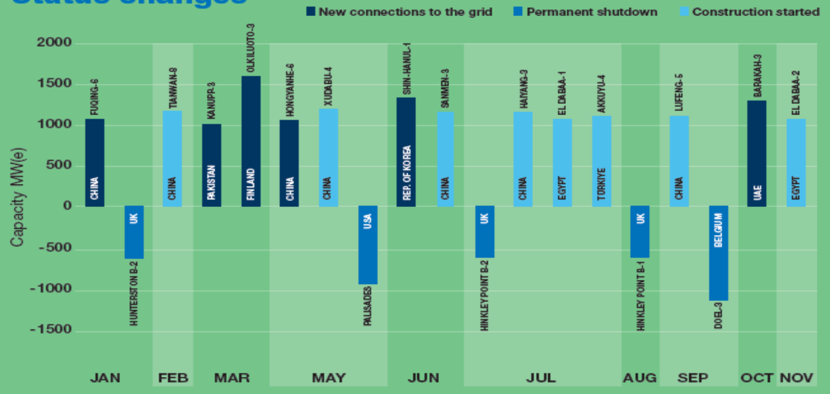
Hydrogen production***

Desalination **41** GWh electrical equivalent of heat

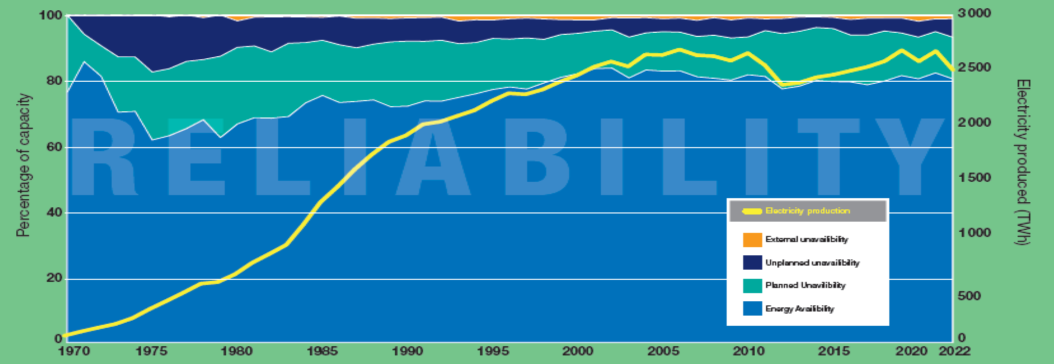
resulted in approximately **1.5** billion gallons of water



Status changes



Nuclear power performance



Country statistics

Reactors in operation · Reactors under construction · Net capacity (MW(e)) · Electricity produced (TWh) · Nuclear share

Country	Reactors in operation	Net capacity in operation (MW(e))	Reactors under construction	Net capacity under construction (MW(e))	Nuclear share	Electricity produced (TWh)
Argentina	3	1641	1	25	5.4%	7.5
Egypt	0	0	2	2200	NA	NA
Netherlands	1	482	0	0	3.3%	3.9
Armenia	1	416	0	0	31.0%	2.6
Finland	5	4394	0	0	35.0%	24.2
Pakistan	6	3262	0	0	16.2%	22.2
Bangladesh	0	0	2	2160	NA	NA
France	56	61370	1	1630	62.6%	282.1
Romania	2	1300	0	0	19.3%	10.2
Türkiye	0	0	4	4456	NA	NA
Belarus	1	1110	1	1110	11.9%	4.4
Germany	3	4055	0	0	5.8%	31.9
Russia	37	27727	3	2700	19.6%	209.5
Ukraine	15	13107	2	2070	*	*
Belgium	6	4936	0	0	46.4%	41.7
Hungary	4	1916	0	0	47.0%	15.0
Slovakia	4	1968	2	880	59.2%	14.6
United Arab Emirates	3	4011	1	1310	12.3%	19.3
Brazil	2	1884	1	1340	2.5%	13.7
India	19	6290	8	6028	3.1%	42.0
Slovenia	1	688	0	0	42.8%	5.3
United Kingdom	9	5883	2	3260	14.2%	43.6
Bulgaria	2	2006	0	0	32.5%	15.8
Islamic Republic of Iran	1	915	1	974	1.7%	6.0
South Africa	2	1854	0	0	4.9%	10.1
United States	92	94718	2	2234	18.2%	772.2
Canada	19	13624	0	0	12.9%	81.7
Japan	10	9486	2	2653	6.1%	51.9
Spain	7	7123	0	0	20.3%	56.2
China	54	52181	20	20284	5.0%	395.4
Republic of Korea	25	24489	3	4020	30.4%	167.5
Sweden	6	6937	0	0	29.5%	50.0
Czech Republic	6	3934	0	0	36.7%	29.3
Mexico	2	1552	0	0	4.5%	10.5
Switzerland	4	2973	0	0	36.4%	23.2

Taiwan, China: 3 reactors, 2859 MW(e) in operation; 0 reactors under construction; 22.9 TWh electricity supplied, 9.1% nuclear share.

* Data were not submitted for the year 2022 by the time of publication.

NA Not Applicable

GW(e) – Gigawatt electric TWh – Terawatt hour GWh – Gigawatt hour Gt – Gigatonne

** The total includes data for reactors where operation remained suspended during the year 2022: India (4 reactors; 639 MW (e)) and Japan (23 reactors; 22 193 MW (e)).

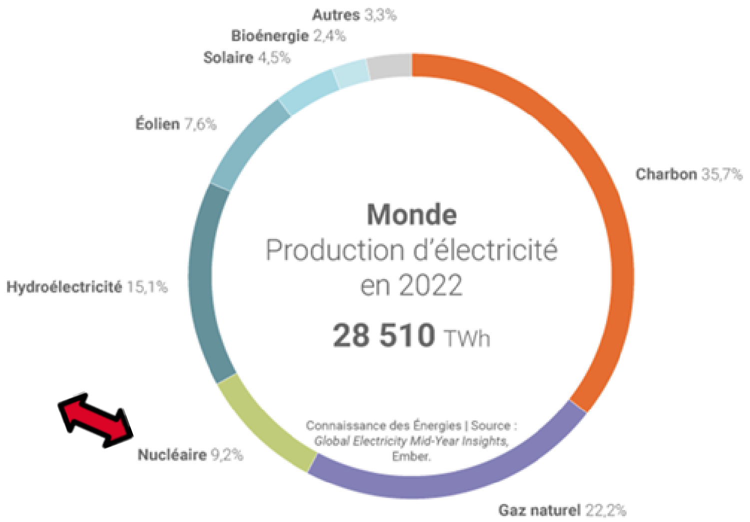
*** Data not available.

22-05239E

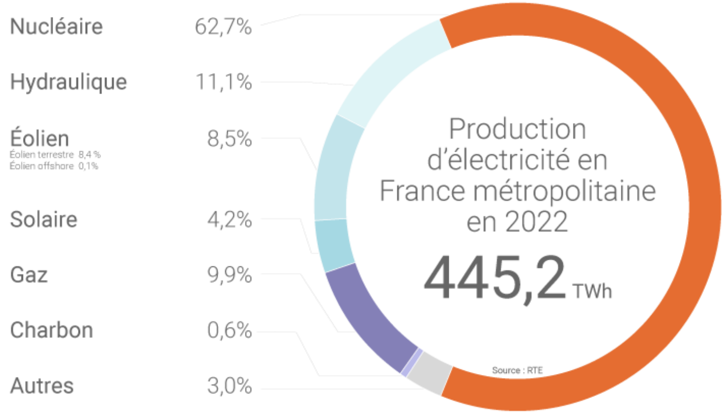
www.iaea.org/pris

442 in the world and 56 in France so far…

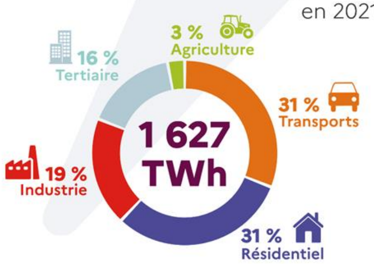
< 4 % de la consommation totale d'énergie



< 20 % de la consommation totale d'énergie



Consommation finale énergétique en 2021

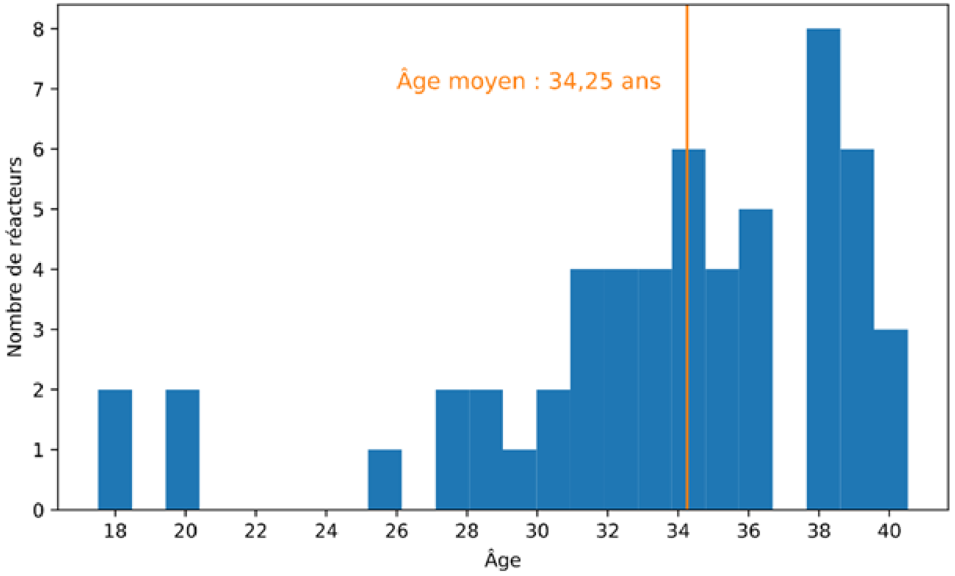


Puissance	Nombre de réacteurs
1 450 MW	4
1 300 MW	20
900 MW	32

Nombre de réacteurs nucléaires en France par puissance

Source : EDF 2020

© EDF



The future will be Electrical…or it will not be

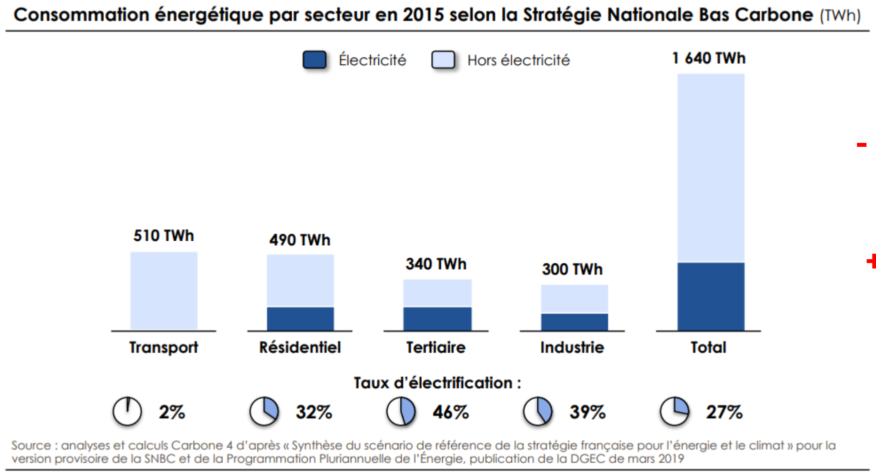


Figure 3 : Consommation énergétique par secteurs en 2015 selon la Stratégie Nationale Bas Carbone (TWh)
Hors pertes et autoconsommation du secteur énergétique

- 40% Tot

+20% Elec

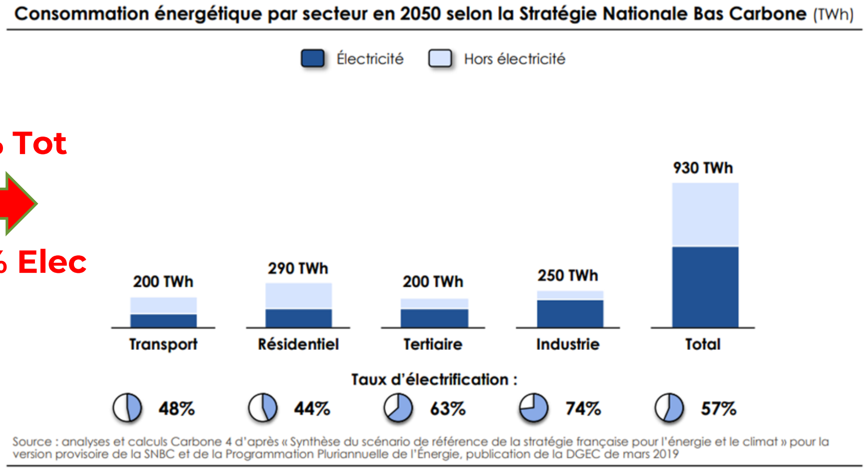
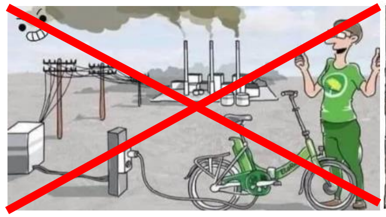


Figure 4 : Consommation énergétique par secteur en 2050 selon la Stratégie Nationale Bas Carbone (TWh)
Hors pertes et autoconsommation du secteur énergétique, hors consommation électrique pour la production d'hydrogène

Carbon Neutrality

The world will need more than 15 GW of new nuclear every year until 2070 according to IEA



The French Nuclear Energy Epopee

Numb. of reactors #56
 # 56 PWRs;
360,9 TWh
~ 69,% of Electricity
~ 92% Low Carbone Emission

Total power* (Gwe)

61.3 (2020)
54.2 (1990)
13.6 (1980)
0

Advanced LWRs

SMR/AMR

-Enhanced Safety
-Highly Economical
-Reducing wastes
-Proliferation resistant

Generation IV

Commercial reactors

Generation III & III+

AP600
System 80+
CANDU6
ABWR
ACR1000
AP1000
EPR
ESBWR

Early prototypes

Generation II

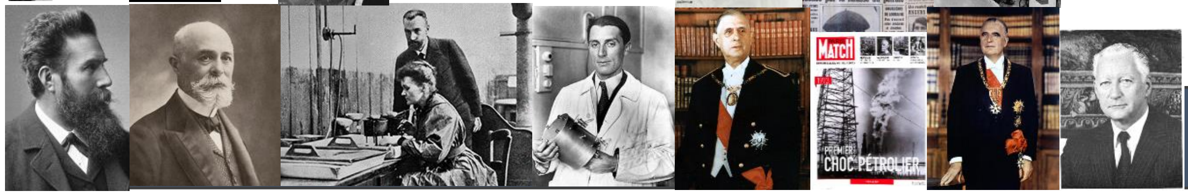
PWR
REP900
REP1300
N4
AGR
BWR
CANDU
RBMK

Generation I

UNGG
ChoozA
Magnox

Zoé, the 1st French nuclear reactor

F. Perrin & M. Curie



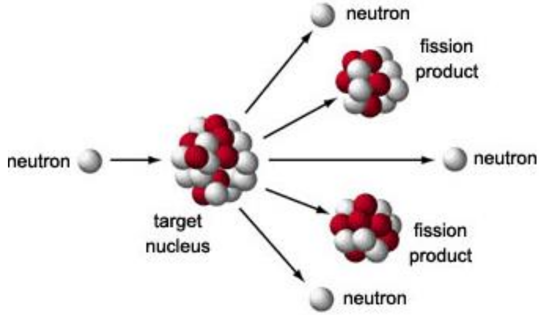
W. Röntgen | H. Becquerel | P. and M. Curie | F. Joliot | Ch. De Gaulle | G. Pompidou | Pierre Messmer

1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050

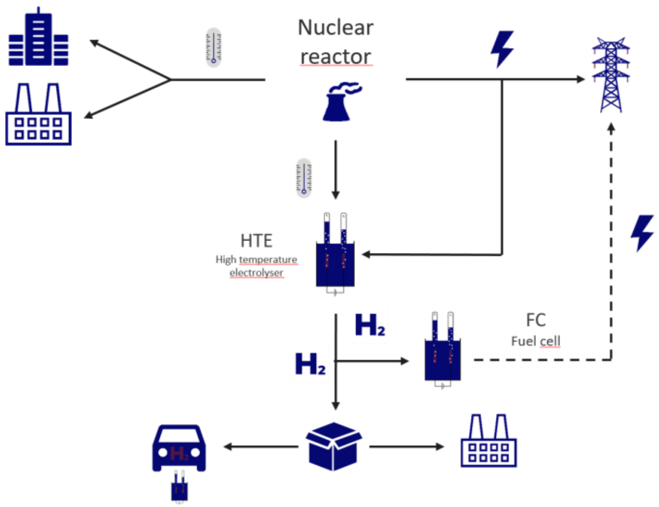
(*)https://cnpp.iaea.org/countryprofiles/France/France.htm

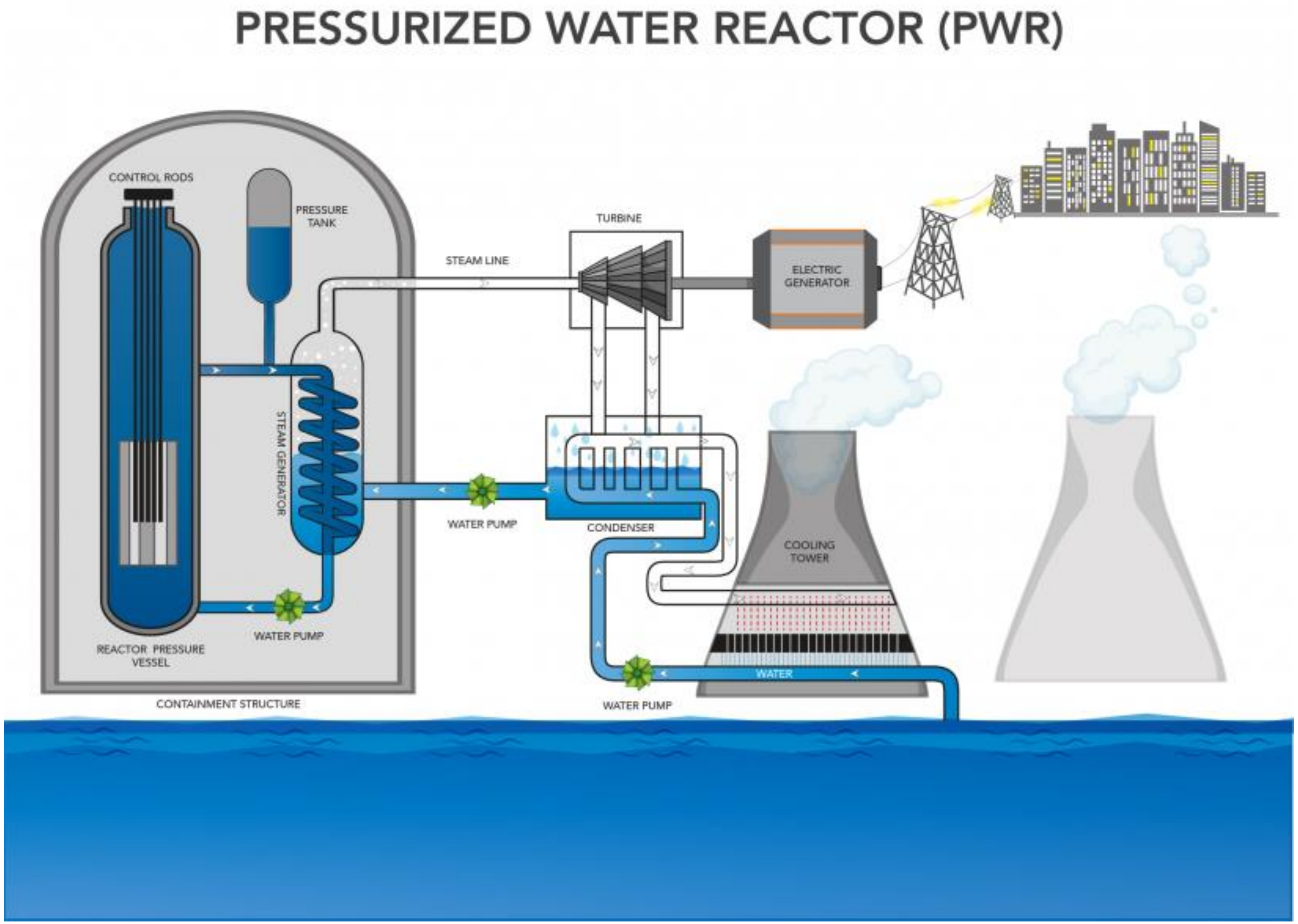
France Equiped only with PWRs

Induced fission



Example of multi-energy use of a nuclear reactor.





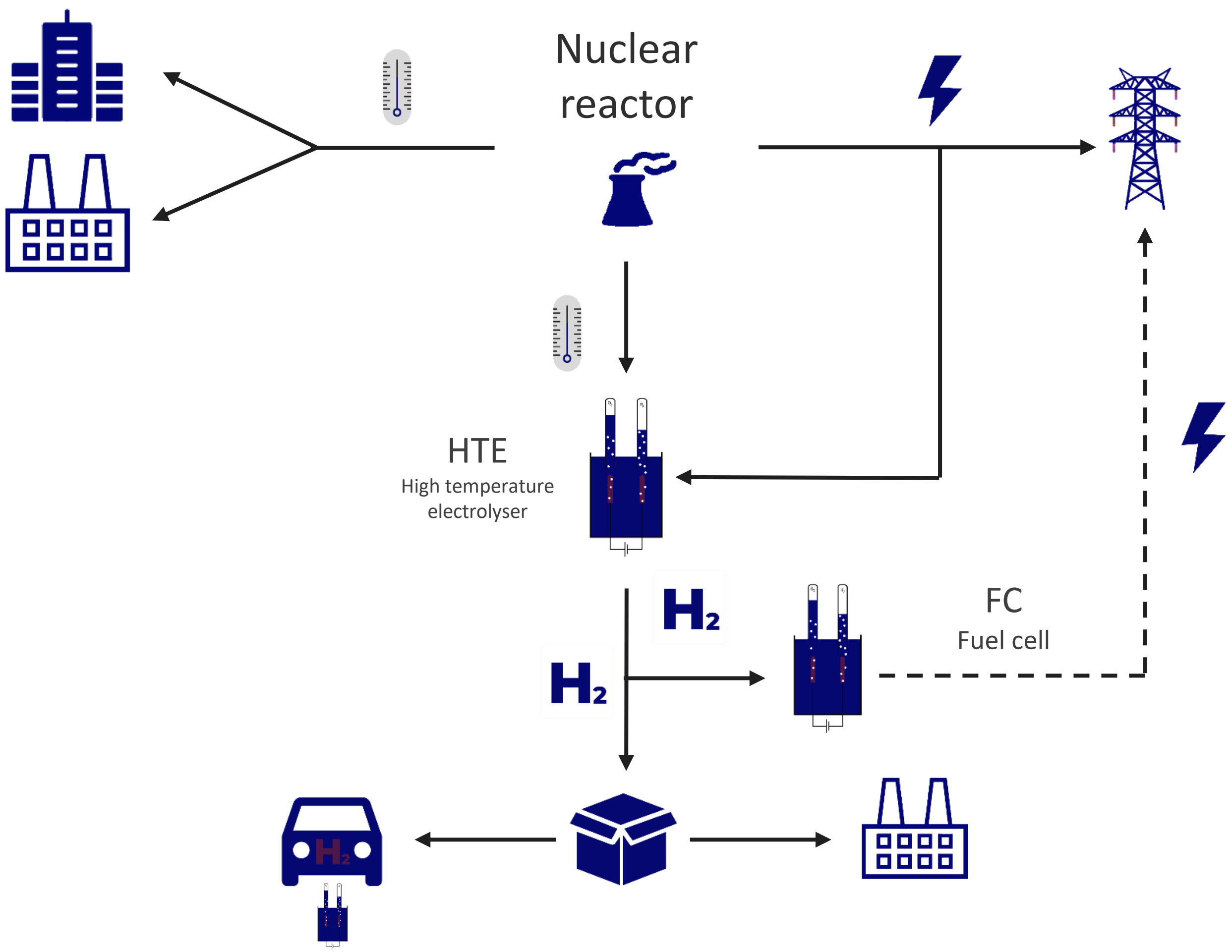
Reactor flexibility and load following.

- Development of more flexible fuels (IPG risk)
- Reactor and power grid studies
- Thermal storage for flexibility

Other energy vectors, storage.

- Non-electric uses of reactors: heat sources, H2, ...
- SMR / HTE coupling, dedicated heat generator SMR ...
- Cogeneration, thermal storage

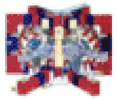
Example of multi-energy use of a nuclear reactor.



AND....The Fusion Nuclear Energy

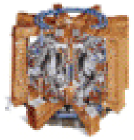
Tore Supra

WEST



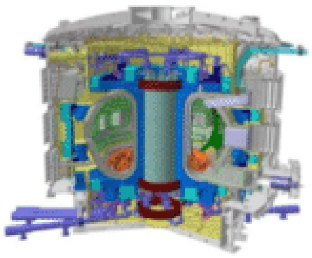
$D = 4.8$ m
$V = 25$ m^3
$Q \approx 0$
$P \approx 0$ MW$_{th}$

JET



$D = 5.92$ m
$V = 80$ m^3
$Q \approx 0.6$
$P \approx 16$ MW$_{th}$

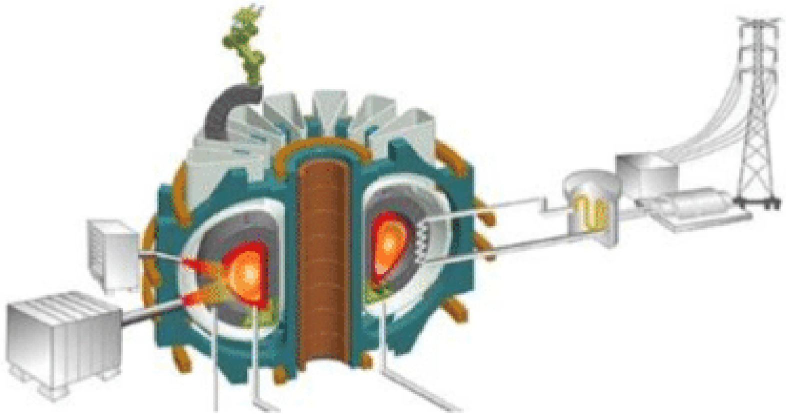
ITER



$D = 12.4$ m
$V = 800$ m^3
$Q \approx 10$
$P \approx 500$ MW$_{th}$

2029

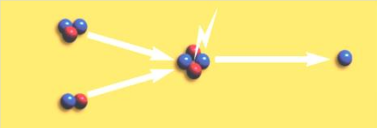
DEMO



$D \approx 13\text{–}19$ m
$V \approx 1000\text{–}3500$ m^3
$Q \approx 25$
$P \approx 2000\text{–}4000$ MW$_{th}$

2060

The Fusion : From Tore Supra to DEMO



See Mike Walsh Presentation