CO_2-free Hydrogen production: the Nuclear route

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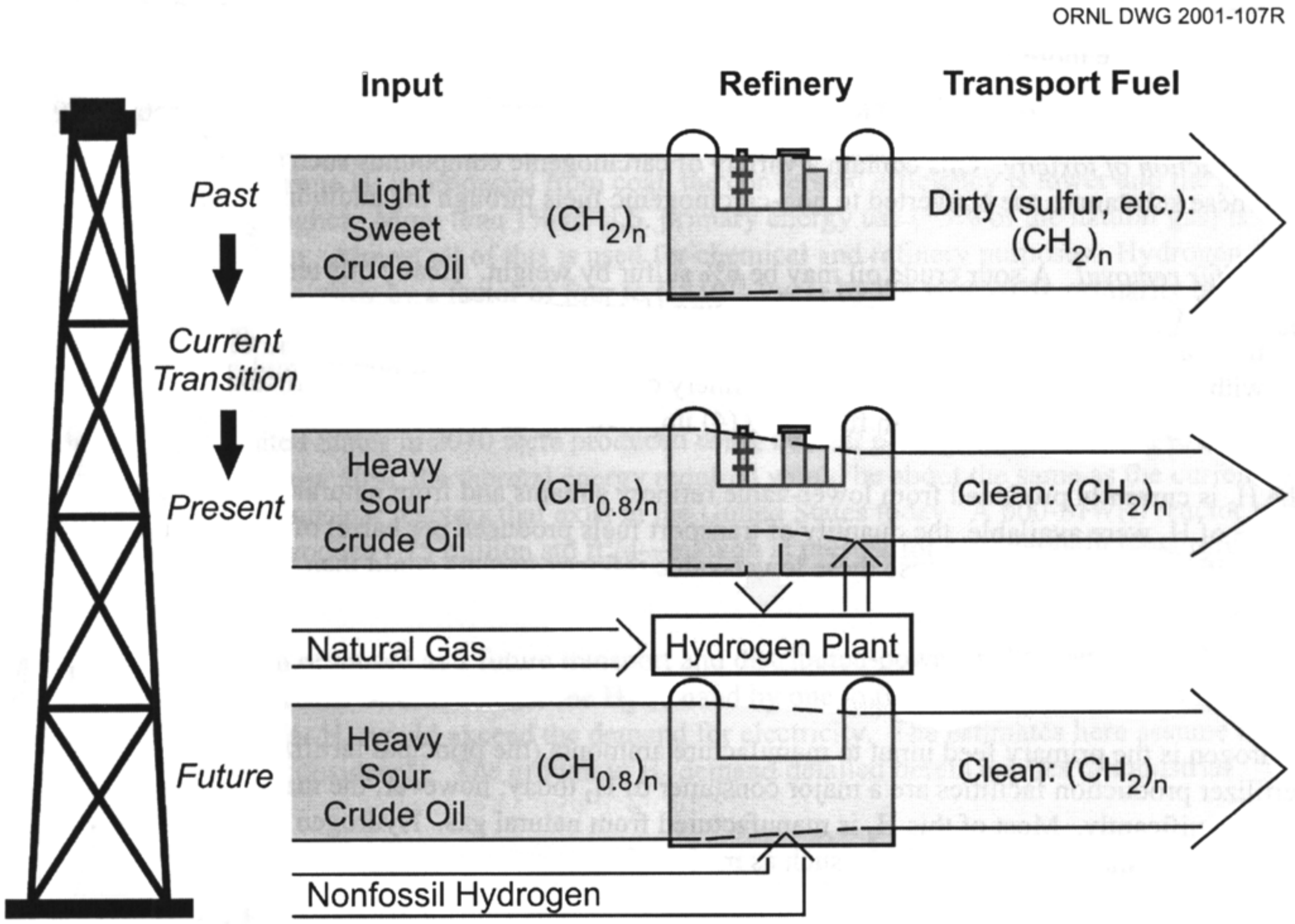
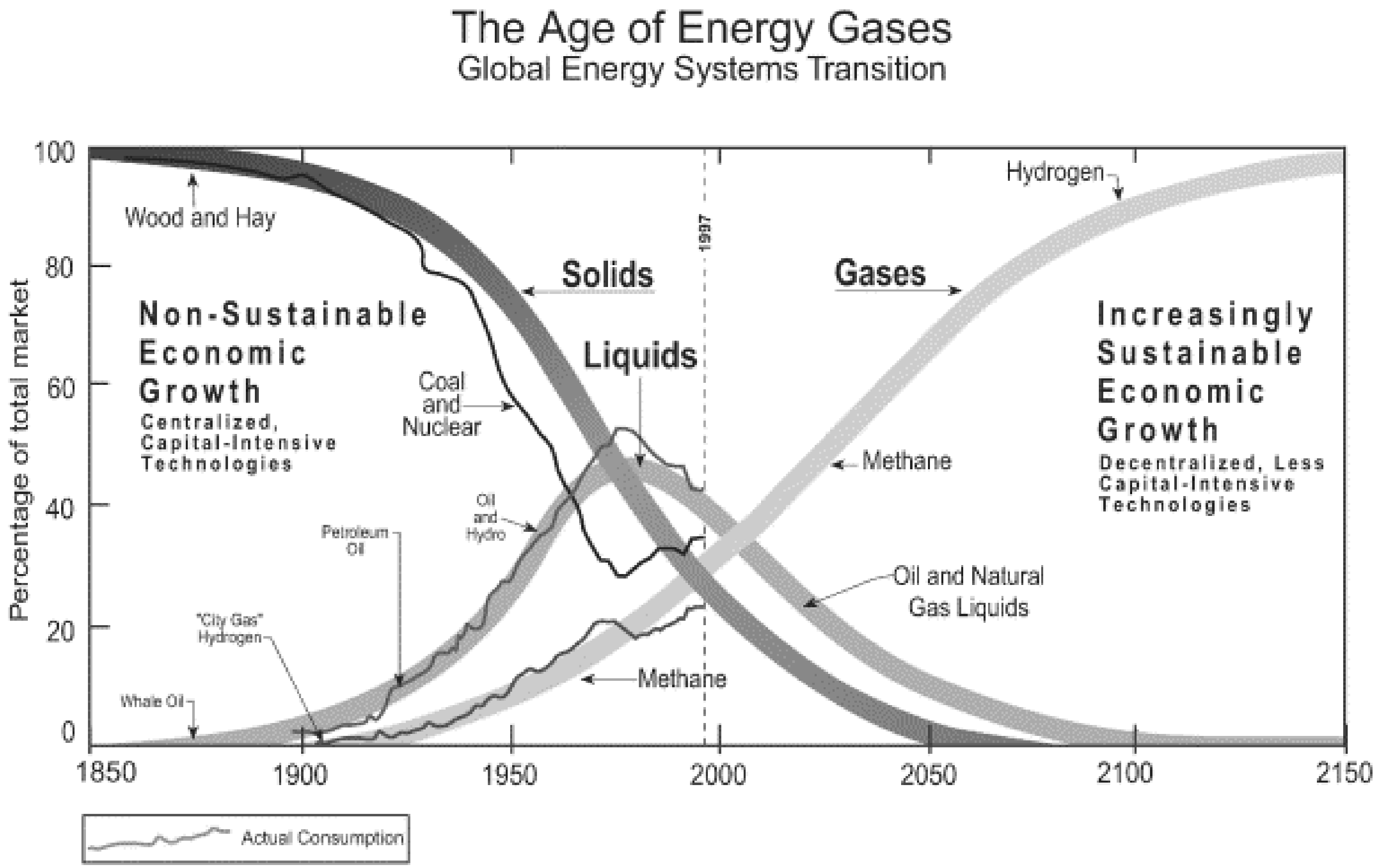
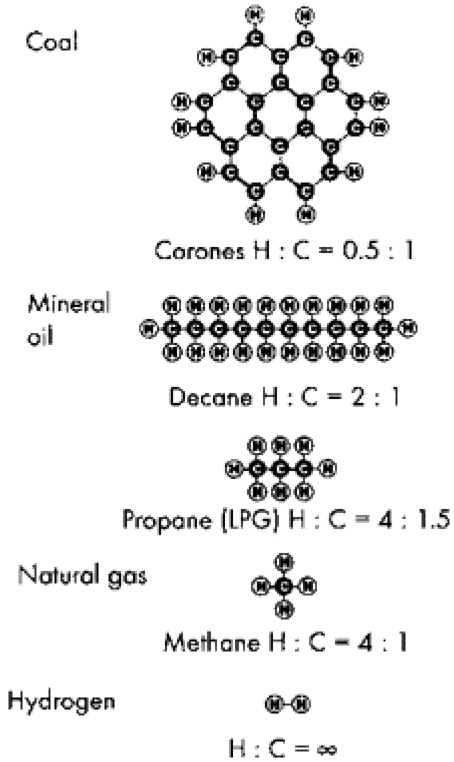
Hydrogen-Carbon ratio in energy mix

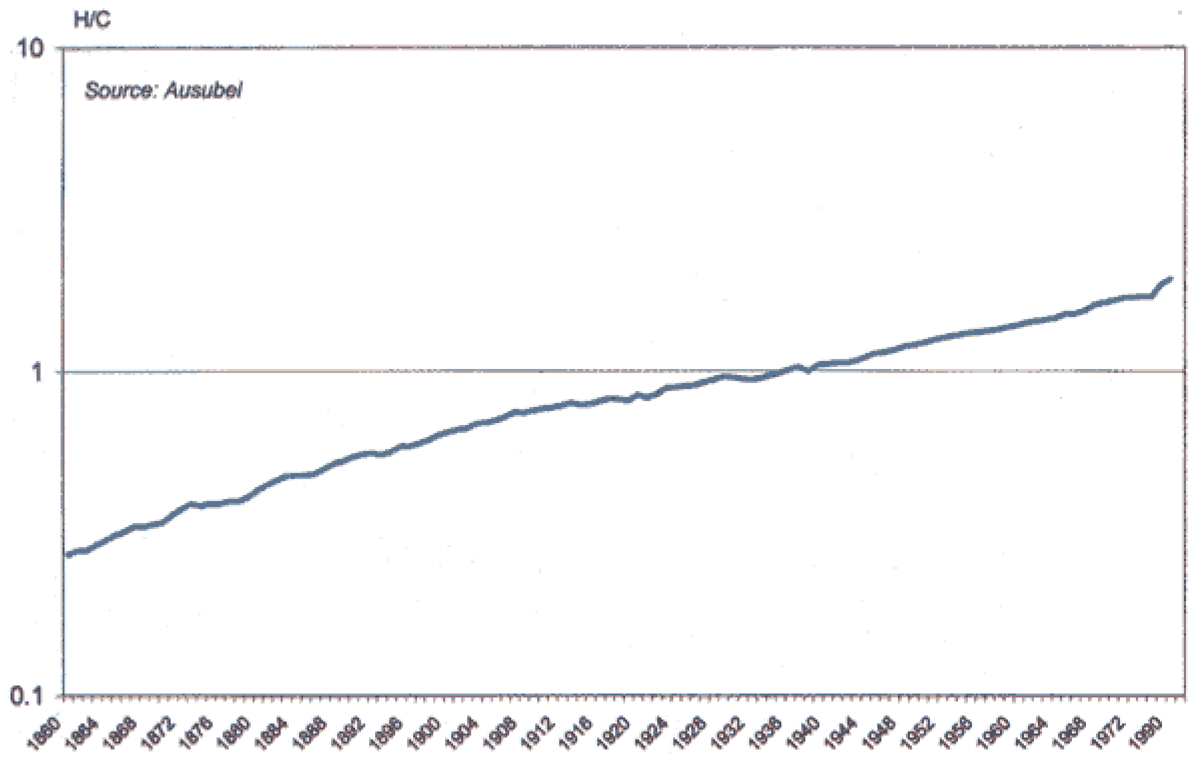


Shares in primary energy

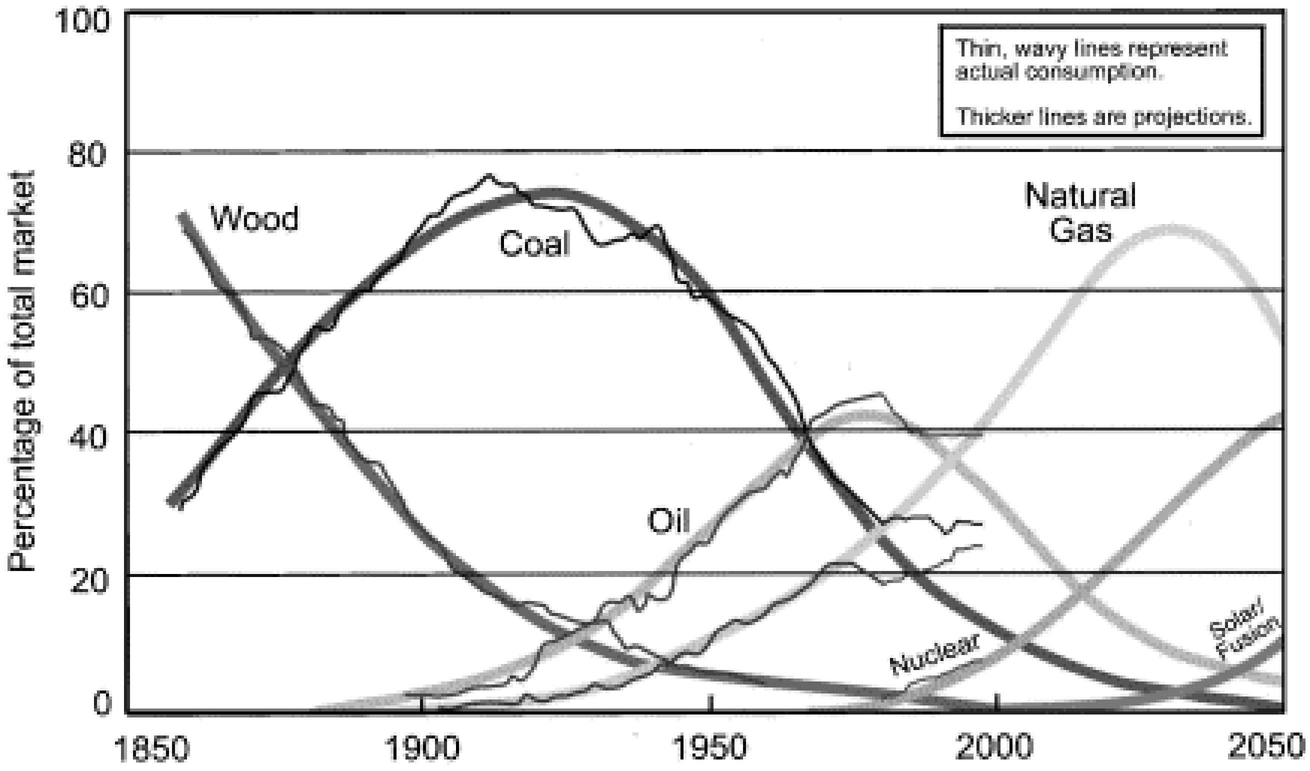


Hydrogen-Carbon ratio in energy mix





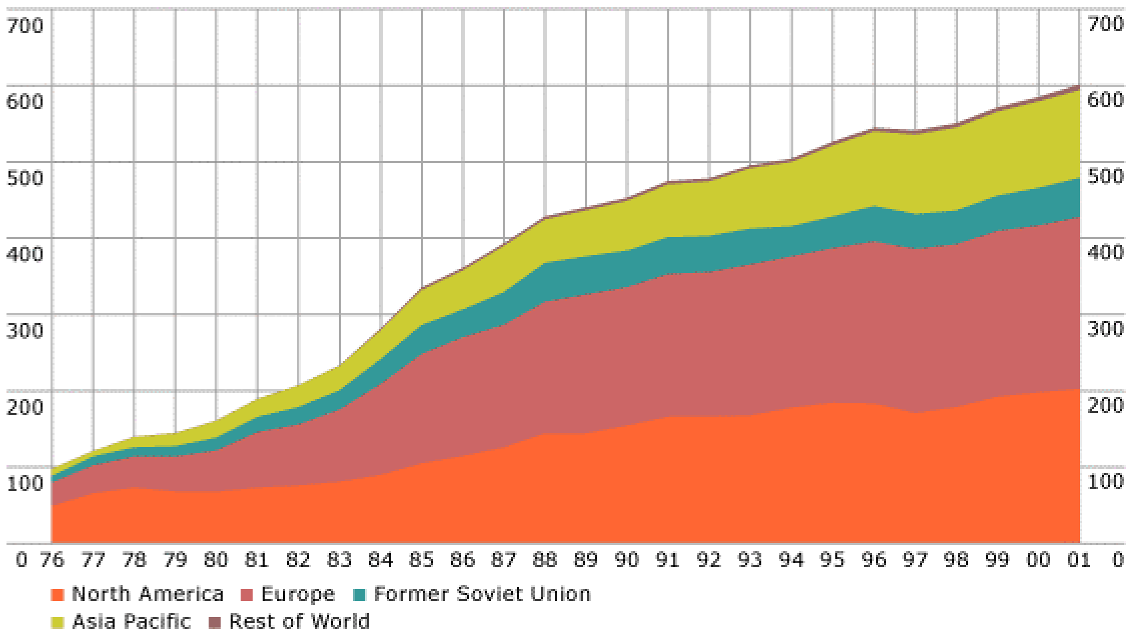
Shares in primary energy



Nuclear energy consumption

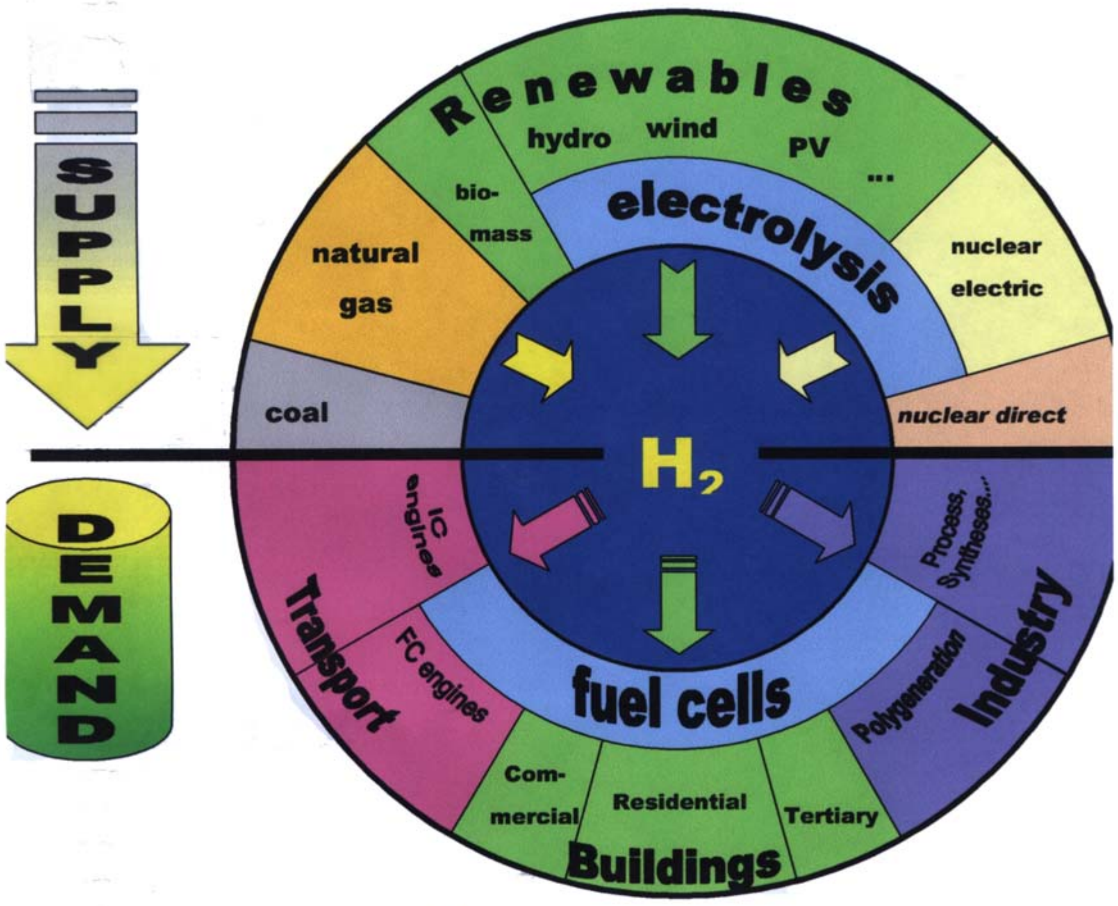
chart of nuclear energy consumption by area

Million tonnes oil equivalent



Nuclear energy maintained its record of steady growth during 2001, registering a 2.8% increase, somewhat ahead of the 10-year annual average of 2.4%.

Hydrogen: primary energy sources, energy converters and applications

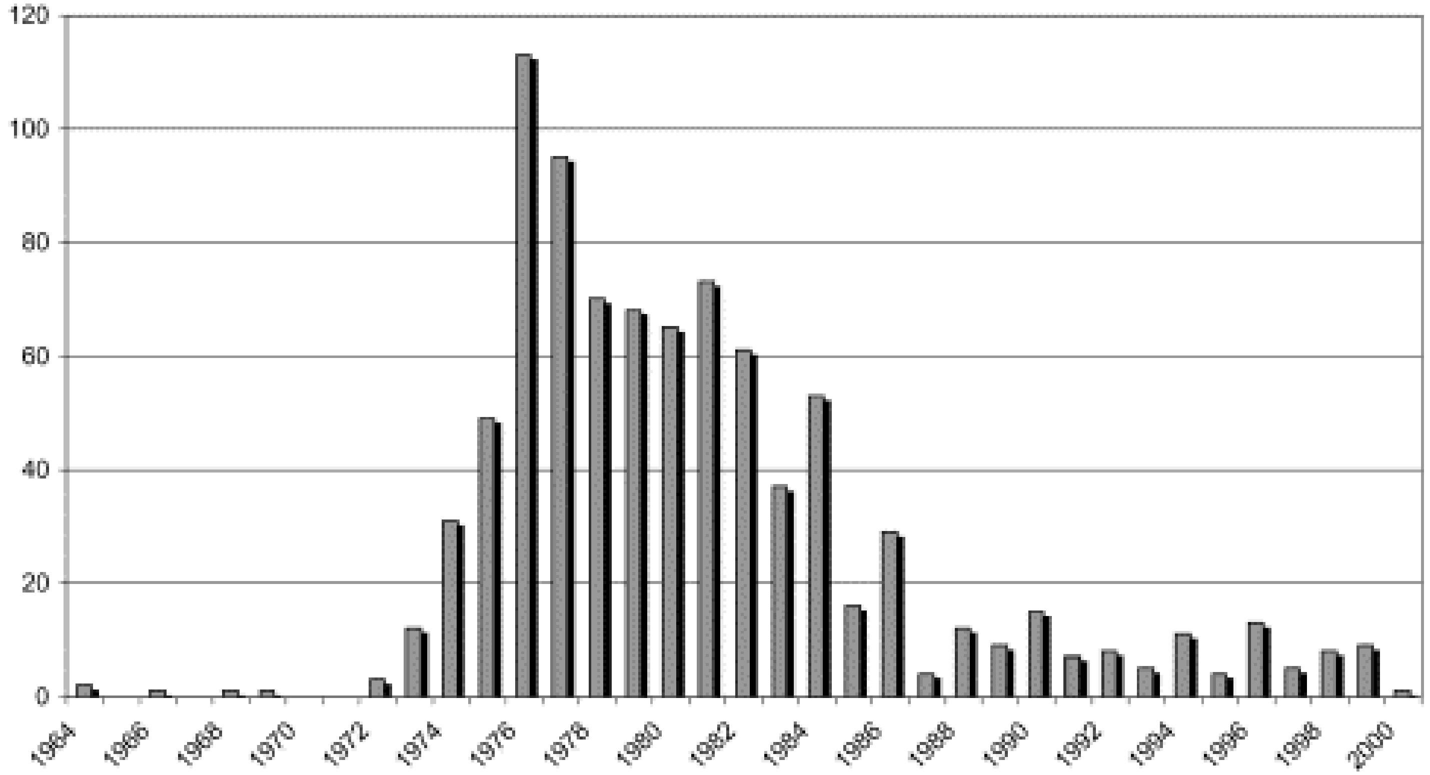


Thermochemical watersplitting

$$H_2O + X \rightarrow XO + H_2$$

$$2XO \rightarrow 2X + O_2$$

Number of publications by year



Metrics used to score TC processes

Metric ⇓ Score ⇒	0	1	2	3	4	5	6	7	8	9	10
1. Number of chemical reactions	6	–	–	5	–	–	4	–	–	3	2
2. Number of chemical separation steps	10	9	8	7	6	5	4	3	2	1	0
3. Number of elements	7		6	–	5	–	4	–	3	2	1
4. Least abundant element in process	Ir	Rh, Te, Os, Ru, Re, Au	Pt, Bi, Pd, Hg, Se	Ag, In, Cd, Sb, Tm, Tl, Lu	I, Tb, W, Ho, U, Ta, Mo, Eu, Cs, Yb, Er, Hf, Sn, Ge	Th, As, Gd, Dy, Sm, Pb, Pr	Nb, Be, Nd, La, Ga, Y, Ce, Co, Sc, Rb	Cu, Zn, Zr, Ni, B, Ba, Li, Br, Cr, V, Sr	Mn, F, P	S, Ti, C, K, N	Ca, Mg, Cl, Na, Al, Fe, Si
5. Relative corrosiveness of process solutions†	Very corrosive, e.g. *aqua* regia		–	–	Moderately corrosive, e.g. sulfuric acid			–	–	–	Not corrosive
6. Degree to which process is continuous and flow of solids is minimized	Batch flow of solids	–	–	Continuous flow of solids	–	Flow of gases or liquids through packed beds			–	Continuous flow of liquids and gases	
7. Maximum temperature in process (°C)	<300 or <1300	300–350 or 1250–1300	350–400 or 1200–1250	400–450 or 1150–1200	450–500 or 1100–1150	500–550 or 1050–1100	550–600 or 1000–1050	600–650 or 950–1000	650–700 or 900–950	700–750 or 850–900	750–850
8. Number of published references to cycle†	1 paper	A few papers			Many papers				Extensive literature base		
9. Degree to which chemistry of cycle has been demonstrated†	No laboratory work	–	–	Test tube scale testing	–	–	Bench scale testing	–	–	–	Pilot plant scale testing
10. Degree to which good efficiency and cost data are available†	No efficiency estimate available		Thermodynamic efficiency estimated from elementary reactions.		Thermodynamic efficiency estimate based on rough flowsheet		Thermodynamic efficiency calculation based on detailed flow sheet		Detailed cost calculations, based on detailed flowsheets aailable from one or more independent sources.		

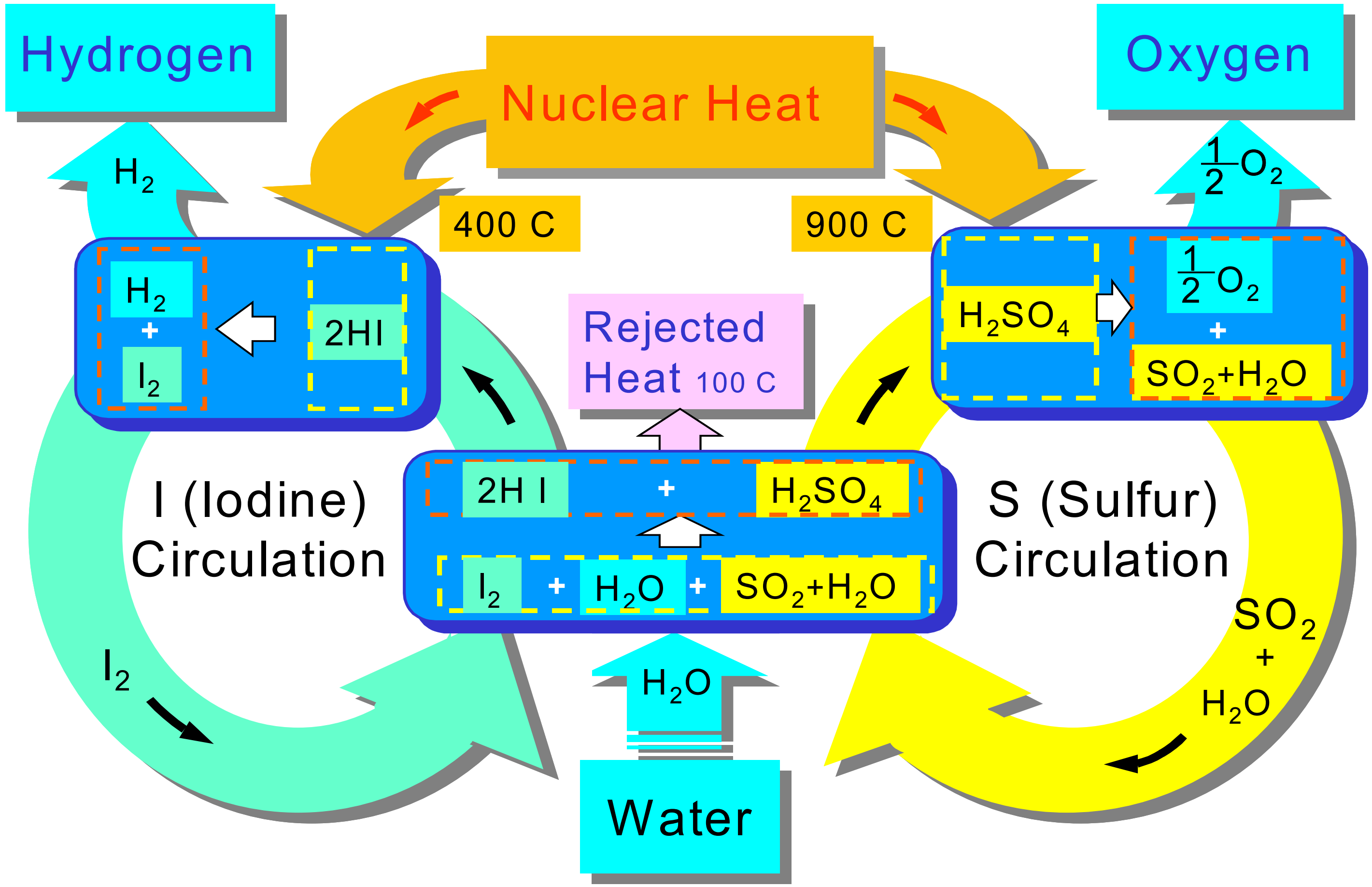
First stage screening score

Cycle#	Name	Class	Max T	Elem	#elem	#seps	#Rxns	Rxns	Seps	Elems	Abund	Corr	Solids	Temp	Pubs	Tests	Data	Total
1	Westinghouse [12]	H	850	S	1	2	2	10	8	10	9	5	10	9	10	6	8	85
2	Ispra Mark 13 [13]	H	850	Br,S	2	3	3	9	7	9	7	5	10	9	10	6	8	80
3	UT-3 Univ. of Tokyo [8]	T	750	Br,Ca,Fe	3	3	4	6	7	8	7	5	6	10	10	10	10	79
4	Sulfur-Iodine [14]	T	800	I,S	2	3	3	9	7	9	4	5	10	10	10	6	8	78
5	Julich Center EOS [15]	T	800	Fe,S	2	3	3	9	7	9	9	9	6	10	3	3	3	68
6	Tokyo Inst. Tech. Ferrite [16]	T	1000	Fe,Mn,Na	3	2	2	10	8	8	8	10	10	6	2	2	0	64
7	Hallett Air Products 1965 [15]	H	800	Cl	1	3	2	10	7	10	10	5	10	10	0	0	0	62
8	Gaz de France [15]	T	825	K	1	3	3	9	7	10	9	5	6	10	2	2	2	62
9	Nickel Ferrite [17]	T	1000	Fe,Ni,Mn	3	0	2	10	10	8	7	10	6	6	0	3	0	60
10	Aachen Univ Julich 1972 [15]	T	800	Cr,Cl	2	3	3	9	7	9	7	5	6	10	2	2	2	59
11	Mark 1C [13]	T	900	Br,Ca,Cu	3	4	4	6	6	8	7	5	10	8	2	3	3	58
12	LASL- U [15]	T	700	C,U	2	3	3	9	7	9	4	10	6	9	1	3	0	58
13	Ispra Mark 8 [13]	T	900	Cl,Mn	2	3	3	9	7	9	8	5	3	8	3	2	3	57
14	Ispra Mark 6 [13]	T	800	Cl,Cr,Fe	3	4	4	6	6	8	7	5	6	10	2	3	3	56
15	Ispra Mark 4 [13]	T	800	Cl,Fe	2	4	4	6	6	9	10	5	0	10	3	3	3	55
16	Ispra Mark 3 [13]	T	800	Cl,V	2	3	3	9	7	9	7	5	0	10	2	3	3	55
17	Ispra Mark 2 (1972) [13]	T	800	C,Na,Mn	3	3	3	9	7	8	8	5	0	10	2	3	3	55
18	Ispra CO/Mn_3O_4 [18]	T	977	C,Mn	2	3	3	9	7	9	8	9	6	7	0	0	0	55
19	Ispra Mark 7B [13]	T	1000	Cl,Fe	2	5	5	3	5	9	10	5	10	6	0	3	3	54
20	Vanadium Chloride [19]	T	700	Cl,V	3	5	4	6	5	8	7	5	6	9	3	2	2	53
21	Ispra Mark 7A [13]	T	1000	Cl,Fe	2	5	5	3	5	9	10	5	6	6	3	3	3	53
22	GA Cycle 23 [20]	T	850	S	2	4	5	3	6	9	9	5	10	9	0	0	0	51
23	US –Chlorine [15]	T	993	Cl,Cu	2	3	3	9	7	9	7	6	5	7	0	0	0	50
24	Ispra Mark 9 [13]	T	450	Cl,Fe	2	8	3	9	2	9	10	5	3	4	2	3	3	50
25	Ispra Mark 6C [13]	T	800	Cl,Cr,Cu,Fe	4	5	5	3	5	6	7	5	6	10	2	3	3	50

Second stage screening scores

Cycle	Name	SNL	UK	GA	Score
1	Westinghouse	1	0	0	1
2	Ispra Mark 13	0	0	0	0
3	UT–3 Univ. of Tokyo	1	1	1	3
4	Sulfur–Iodine	1	1	1	3
5	Julich Center EOS	1	–1	–1	–1
6	Tokyo Inst. Tech. Ferrite	–1	0	0	–1
7	Hallett Air Products 1965	1	–1	0	0
8	Gaz de France	–1	–1	–1	–3
9	Nickel Ferrite	–1	0	0	–1
10	Aachen Univ Julich 1972	0	–1	0	–1
11	Ispra Mark 1C	–1	–1	–1	–3
12	LASL–U	1	–1	–1	–1
13	Ispra Mark 8	0	–1	–1	–2
14	Ispra Mark 6	–1	–1	–1	–3
15	Ispra Mark 4	0	–1	–1	–2
16	Ispra Mark 3	0	–1	–1	–2
17	Ispra Mark 2 (1972)	1	–1	–1	–1
18	Ispra CO/Mn_3O_4	–1	0	0	–1
19	Ispra Mark 7B	–1	–1	–1	–3
20	Vanadium Chloride	0	1	–1	0
21	Mark 7A	–1	–1	–1	–3
22	GA Cycle 23	–1	–1	0	–2
23	US–Chlorine	0	1	–1	0
24	Ispra Mark 9	0	–1	–1	–2
25	Ispra Mark 6C	–1	–1	–1	–3

S-I thermochemical process



S-I thermochemical process

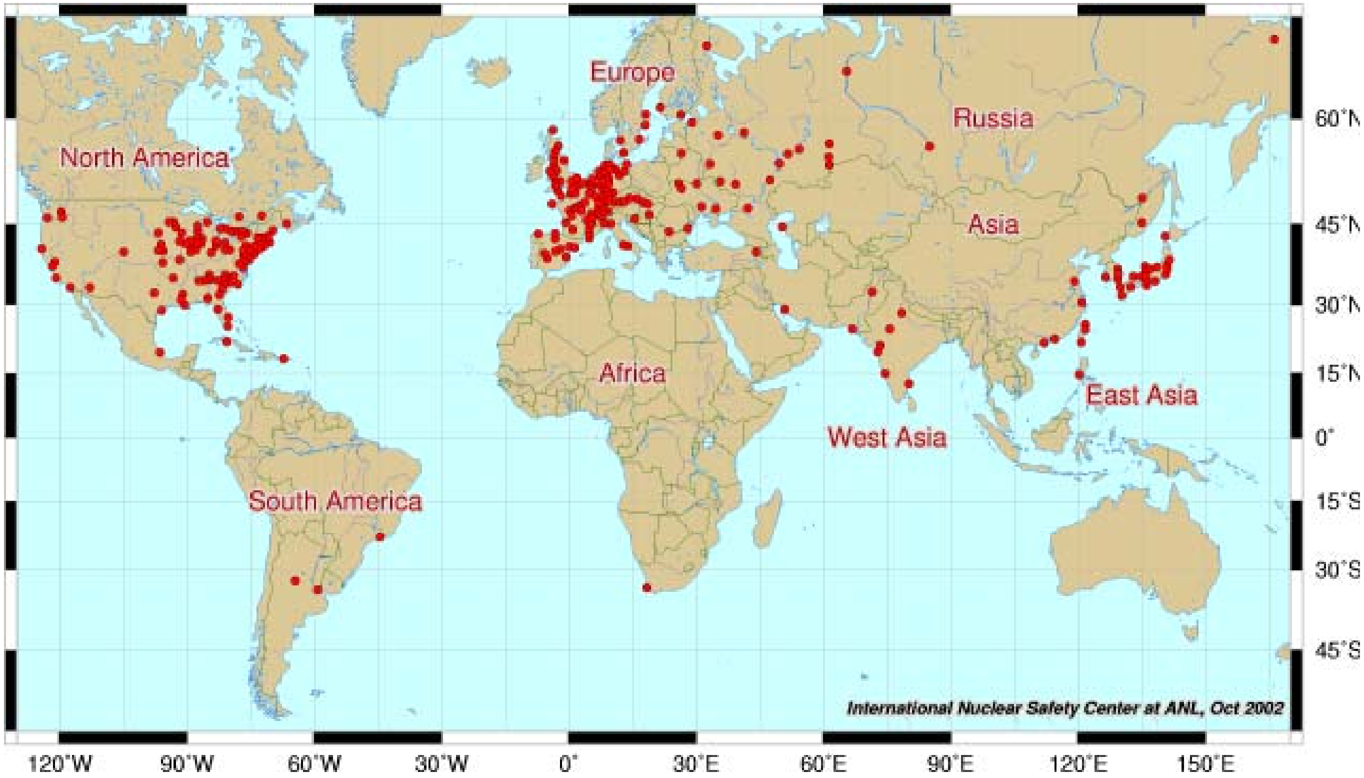
$$2H_2O + SO_2 + I_2 \rightarrow H_2SO_4 + HI$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + O_2$$

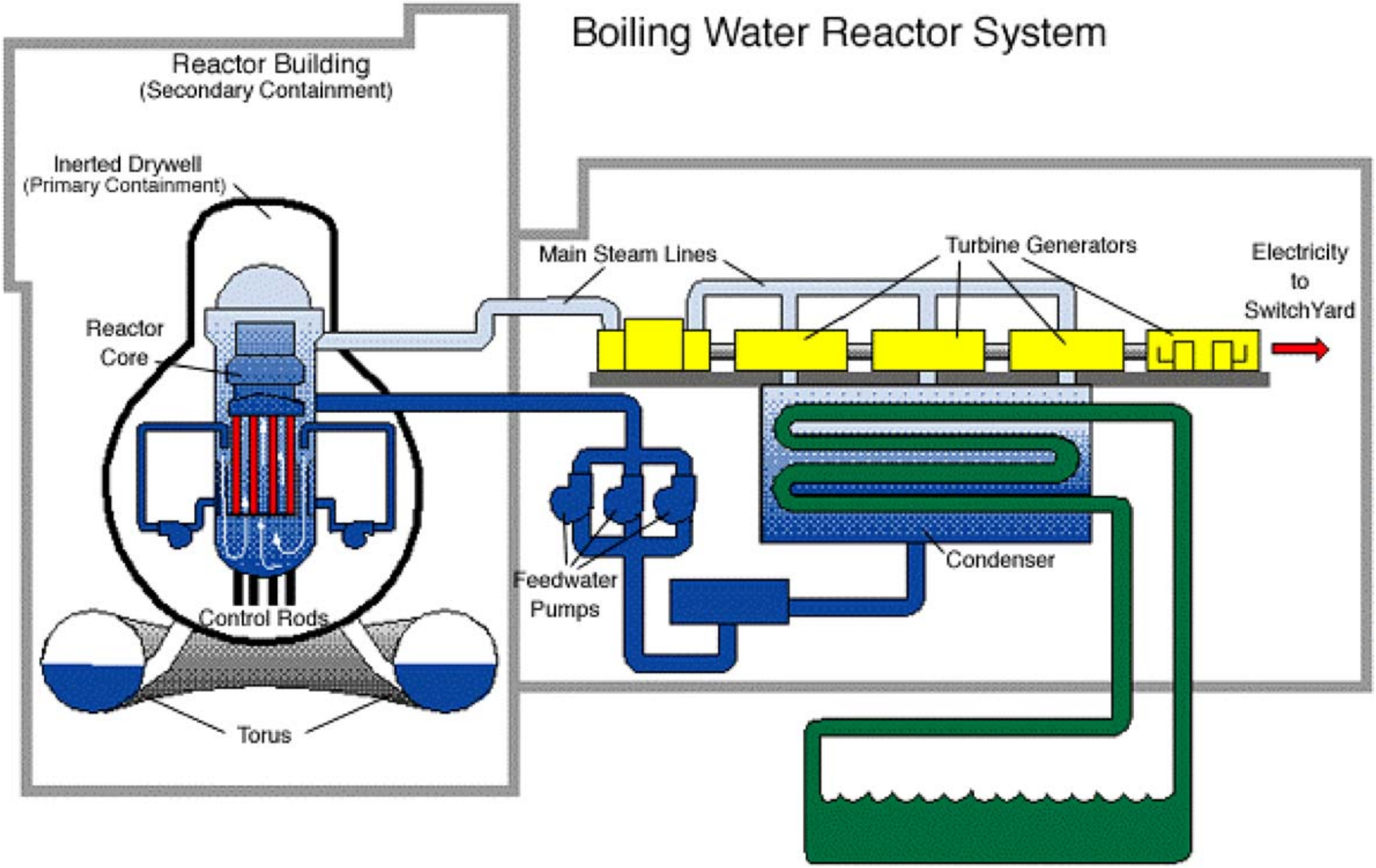
$$2HI \rightarrow H_2 + I_2$$

It's there...

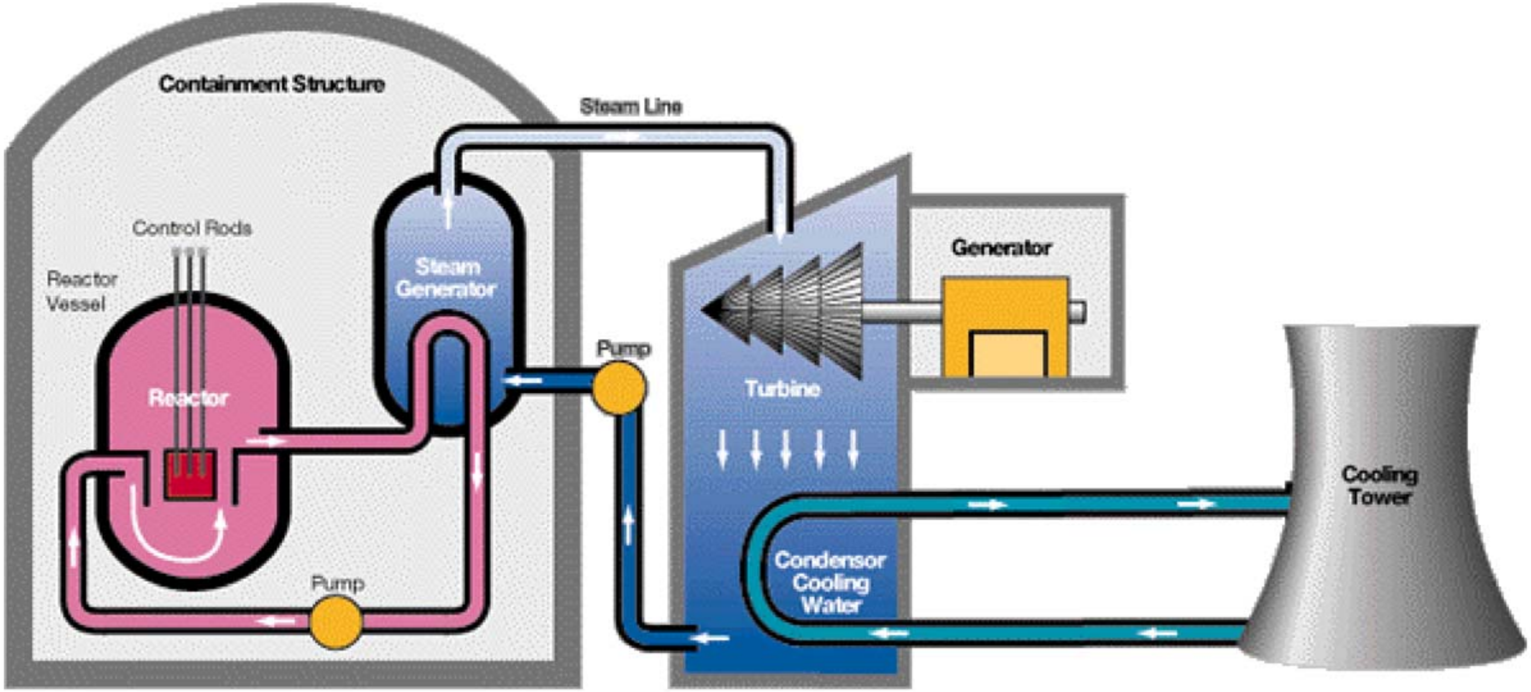
Nuclear reactors in the world



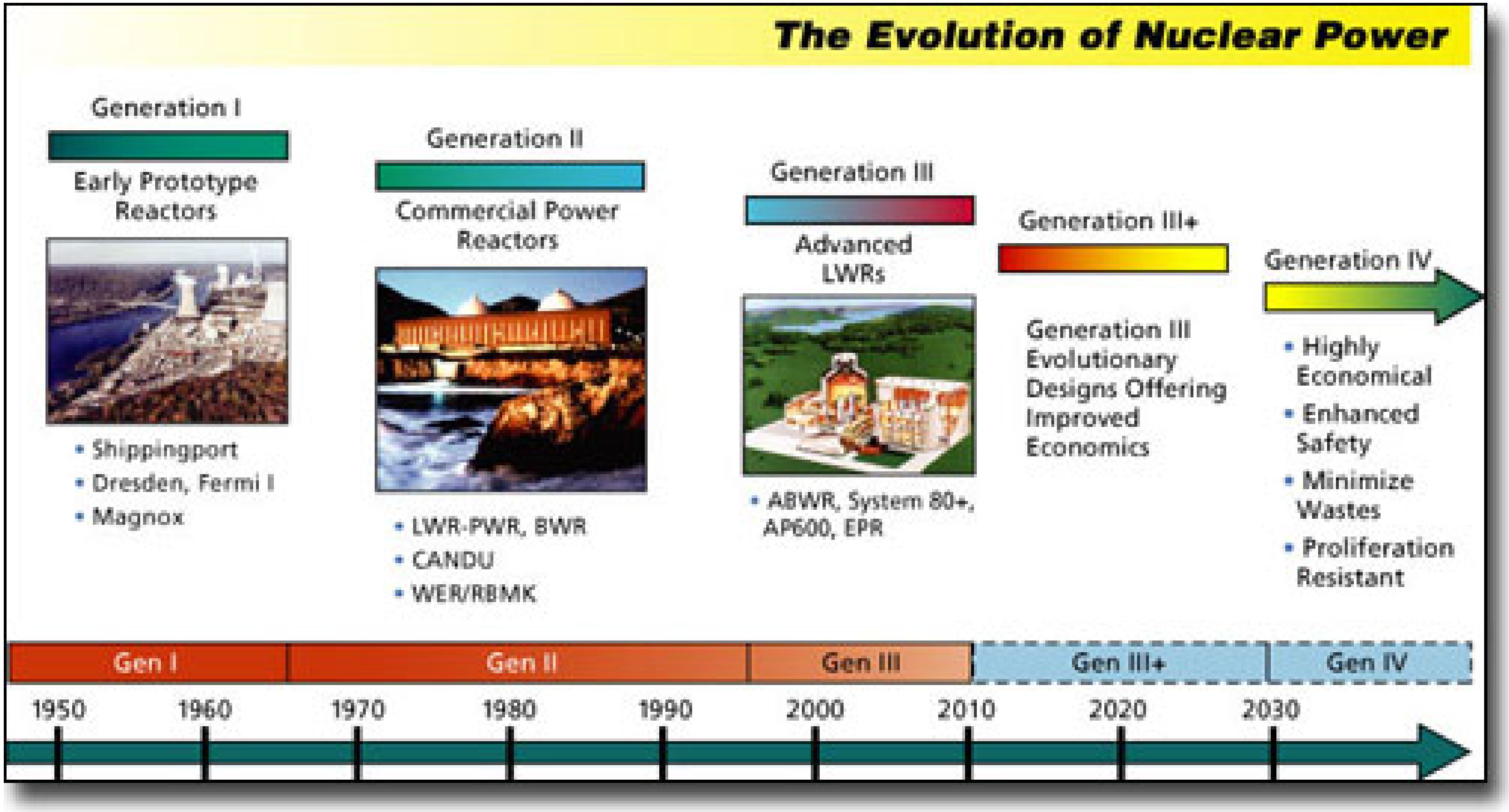
Boiling Water Reactors



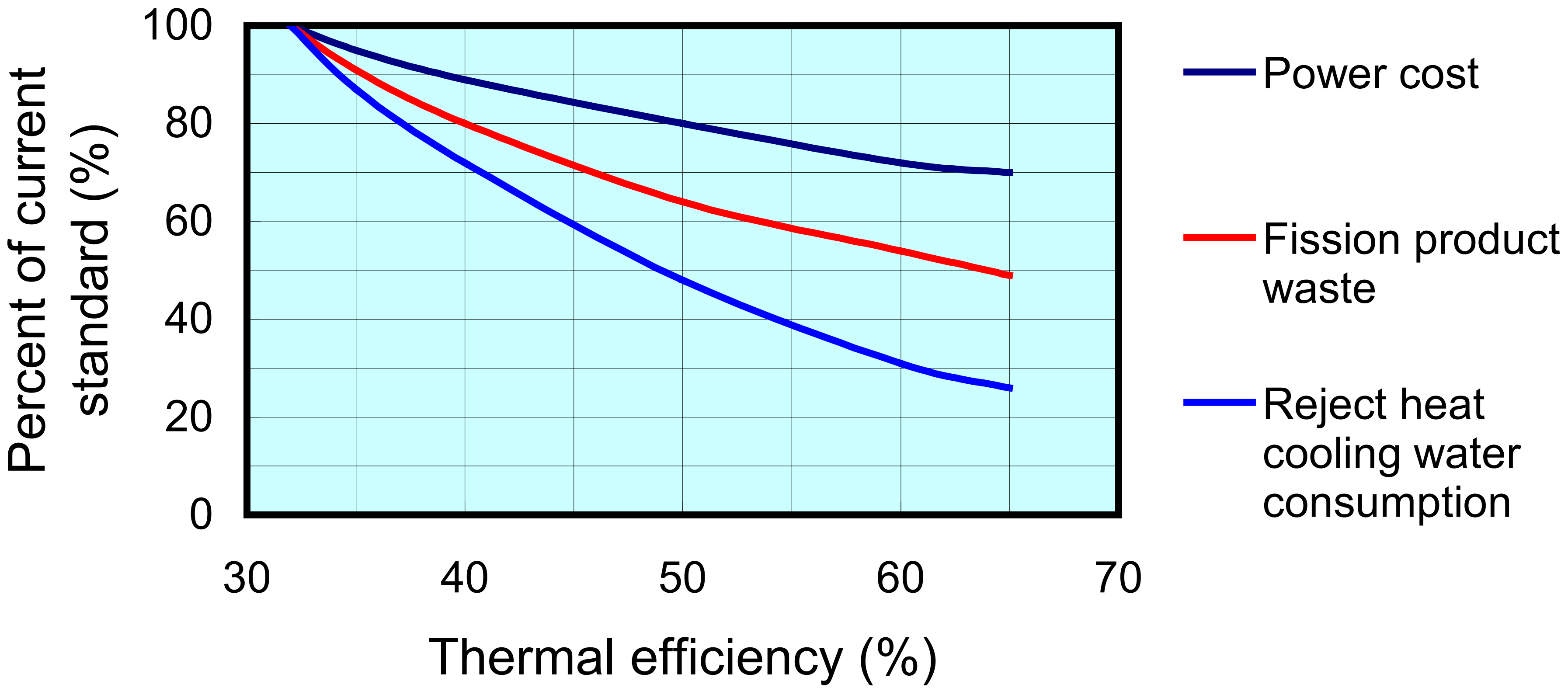
Pressurized Water Reactors



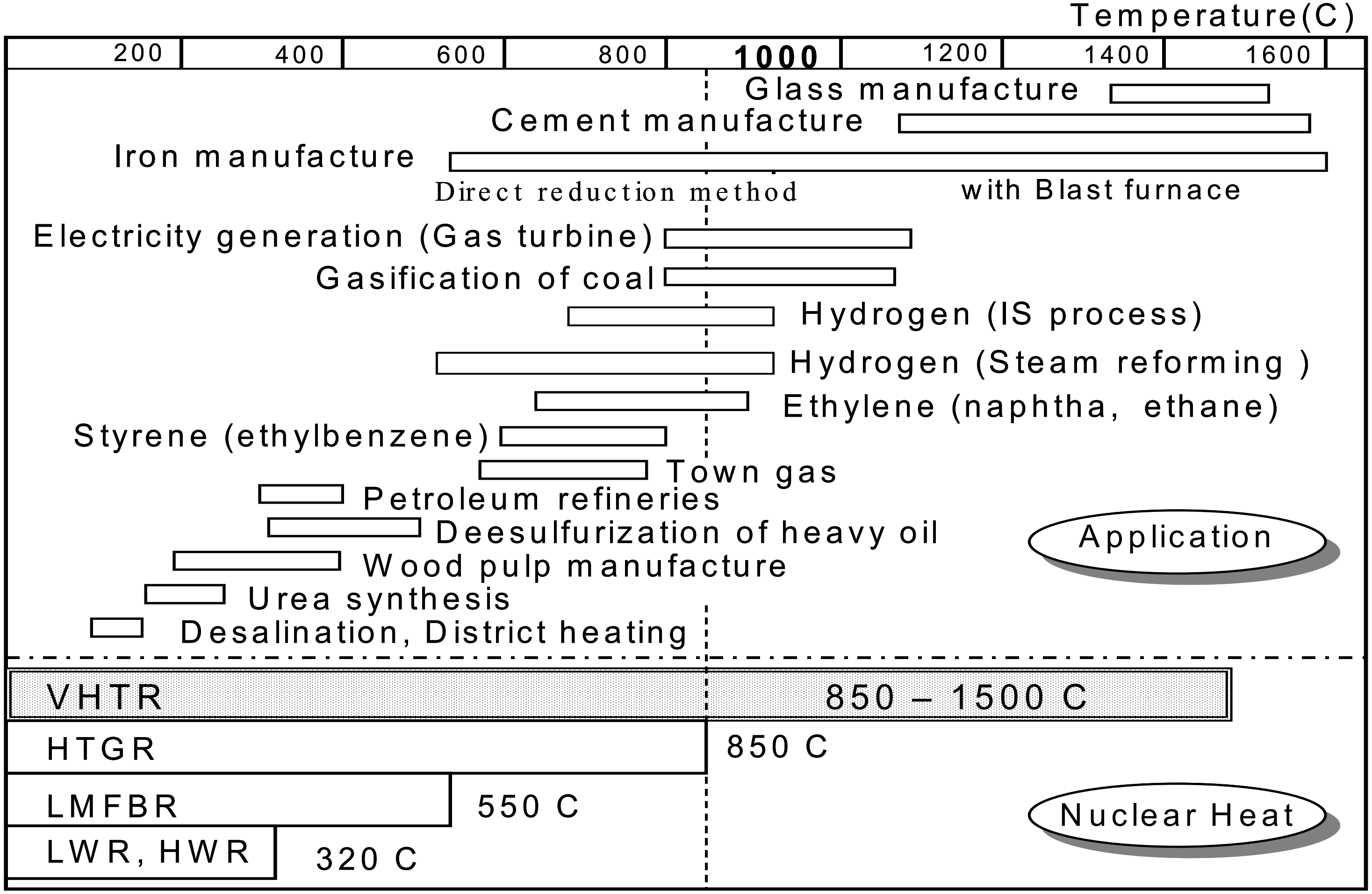
Evolution of nuclear power



Effect of temperature on sustainability



Process Heat Applications

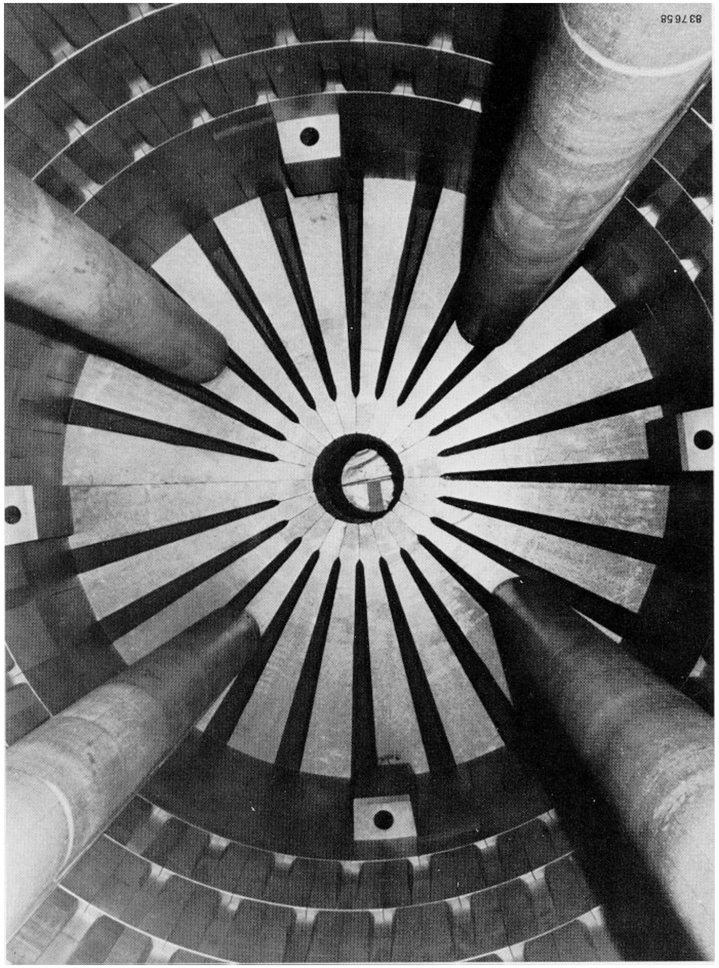


Assessment of reactors for S-I process

Coolant	Gas	Salt	Heavy metal	Liquid core	Alkali metal	PWR	BWR	Org.	Gas core
1. Materials compatibility	4	3	3	3	2	-	0	-	-
2.Coolant stability	4	3	4	3	4	-	-	0	-
3. Operating Pressure	4	4	4	4	4	0	-	-	-
4.Nuclear issues	4	4	4	3	3	-	-	-	-
5. Feasibility	4	3	2	3	2	-	-	-	0
1. Safety	3	4	3	3	2	-	-	-	-
2. Operations	3	3	3	2	3	-	-	-	
3. Capital costs	2	3	3	1	1				
4. Intermediate loop compatibility	4	3	3	3	3	-	-	-	-
5. Other merits and issues	3	3	3	3	3	-	-	-	-
Unweighted Mean Score	3.5	3.3	3.2	2.8	2.7	N/A	N/A	N/A	N/A

Arbeitsgemeinschaft Versuchsreaktor

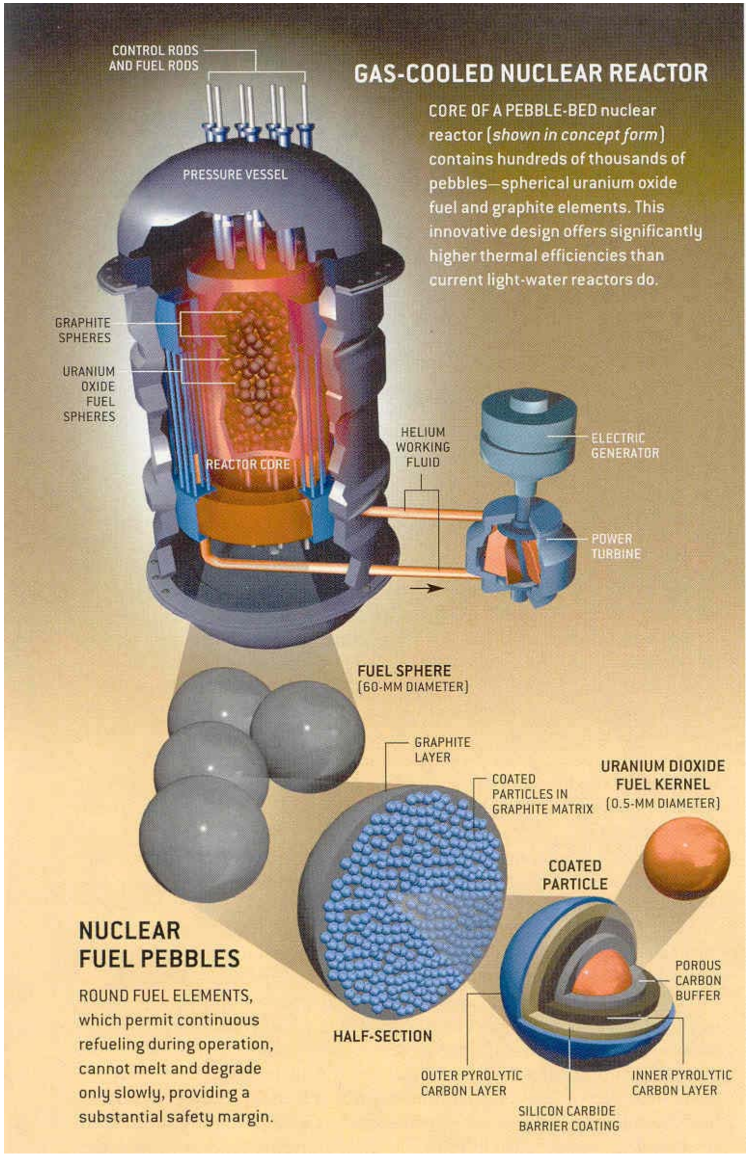
Arbeitsgemeinschaft Versuchsreaktor



Thorium High Temperature Reactor

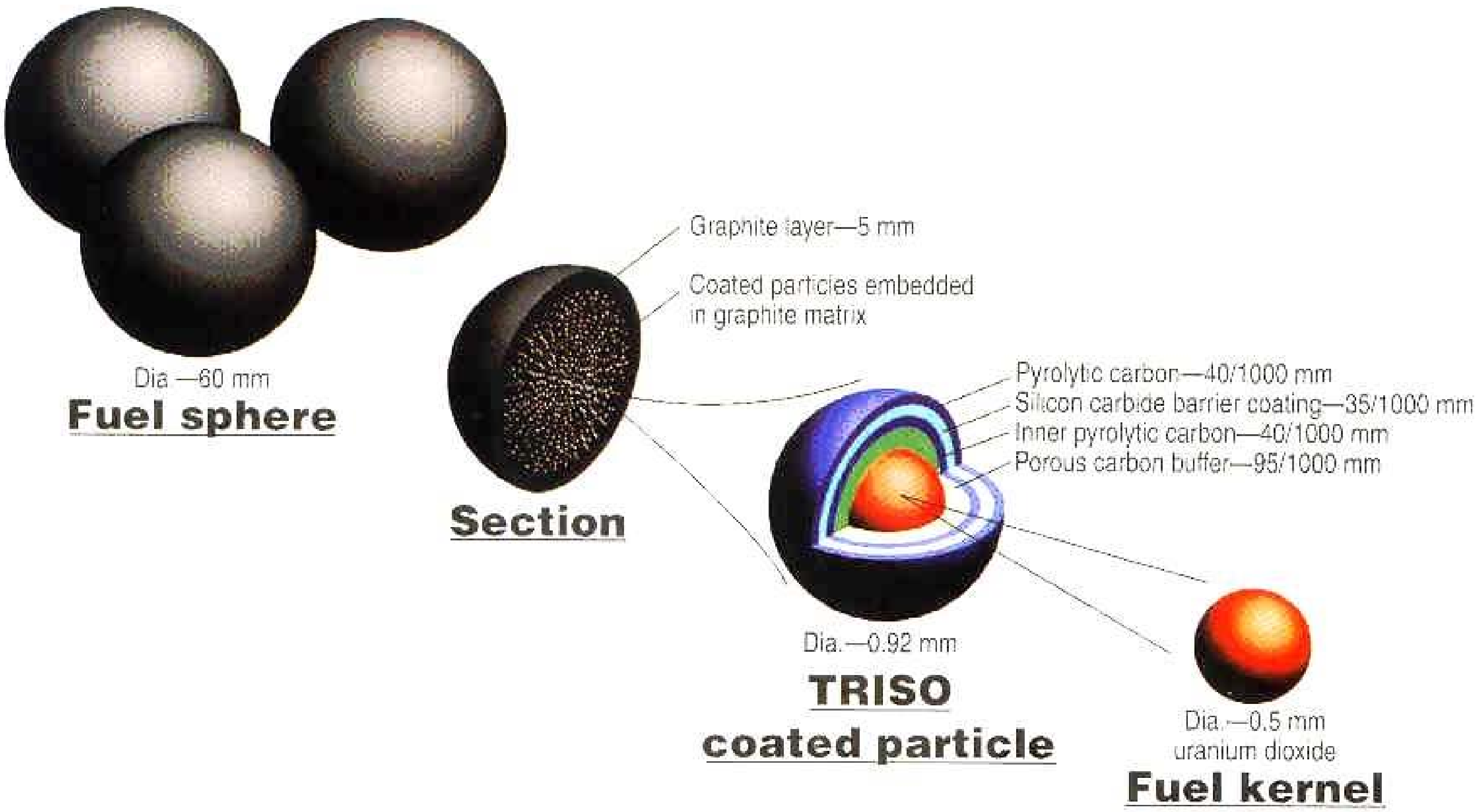
High Temperature Reactors

Project	Description
AVR	15MWe Experimental pebble bed reactor operated for 21 years in Germany
THTR	300 MWe German pebble bed reactor with steam turbine operated for 5 years
Fort St Vrain	330 MWe US HTGR operated for 14 years
HTR-MODUL	80 MWe German modular pebble bed reactor design by Siemens, 1989
HTR-100	100 MWe German modular pebble bed reactor design by HRB/BBC
HTTR	30 MWth Japanese HTGR reached criticality in 1998
HTR-10	10 MWth Chinese HTGR reached criticality in 2000
PBMR	110 MWe South African direct cycle pebble bed design
GT-MHR	300 MWe US direct cycle HTGR design

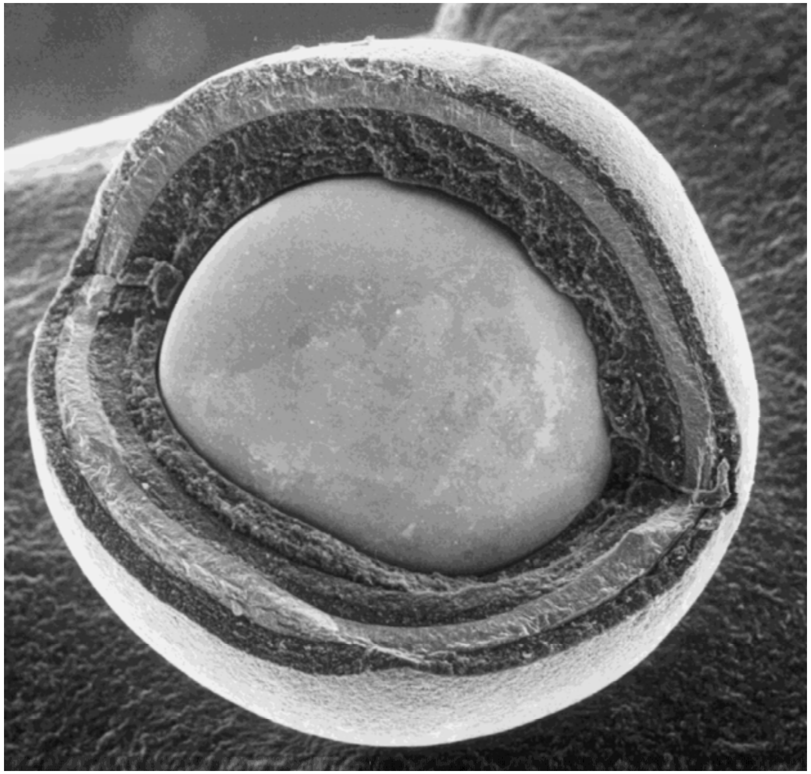


GAS-COOLED NUCLEAR REACTOR
CORE OF A PEBBLE-BED nuclear reactor (shown in concept form) contains hundreds of thousands of pebbles—spherical uranium oxide fuel and graphite elements. This innovative design offers significantly higher thermal efficiencies than current light-water reactors do.
CONTROL RODS AND FUEL RODS
PRESSURE VESSEL
GRAPHITE SPHERES
URANIUM OXIDE FUEL SPHERES
REACTOR CORE
HELIUM WORKING FLUID
ELECTRIC GENERATOR
POWER TURBINE
FUEL SPHERE (60-MM DIAMETER)
GRAPHITE LAYER
COATED PARTICLES IN GRAPHITE MATRIX
URANIUM DIOXIDE FUEL KERNEL (0.5-MM DIAMETER)
COATED PARTICLE
NUCLEAR FUEL PEBBLES
ROUND FUEL ELEMENTS, which permit continuous refueling during operation, cannot melt and degrade only slowly, providing a substantial safety margin.
HALF-SECTION
POROUS CARBON BUFFER
OUTER PYROLYTIC CARBON LAYER
INNER PYROLYTIC CARBON LAYER
SILICON CARBIDE BARRIER COATING

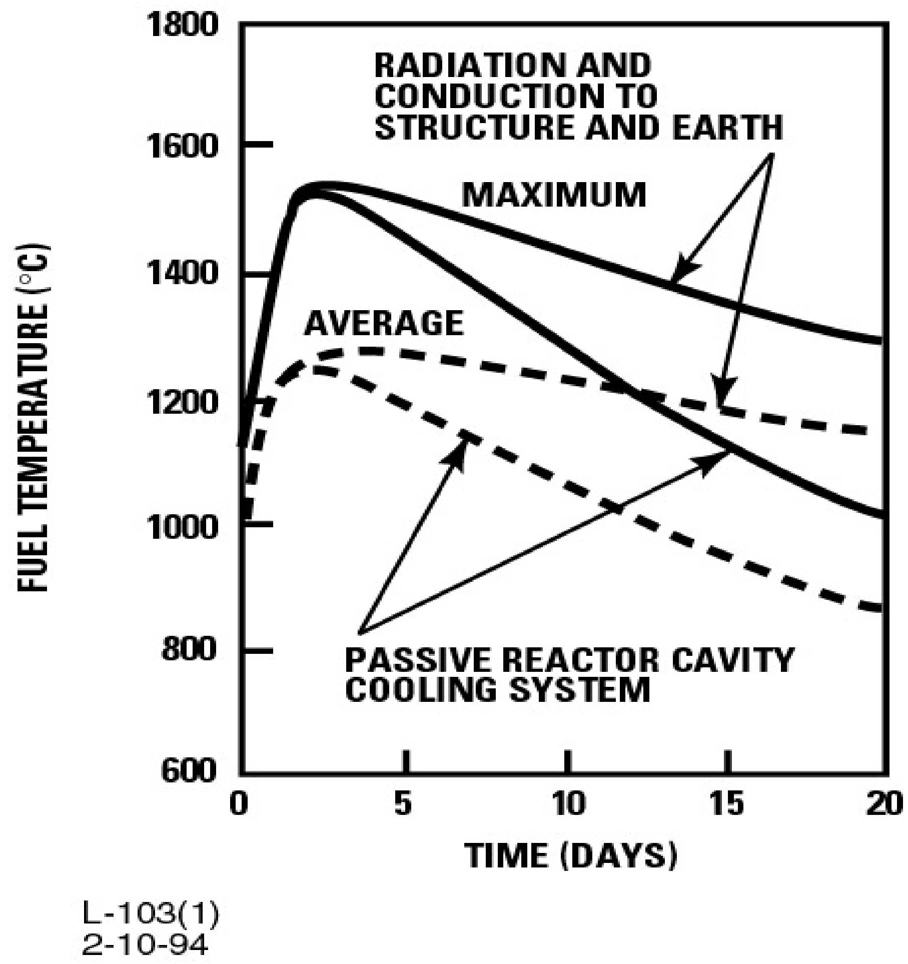
Pebble-bed reactor fuel



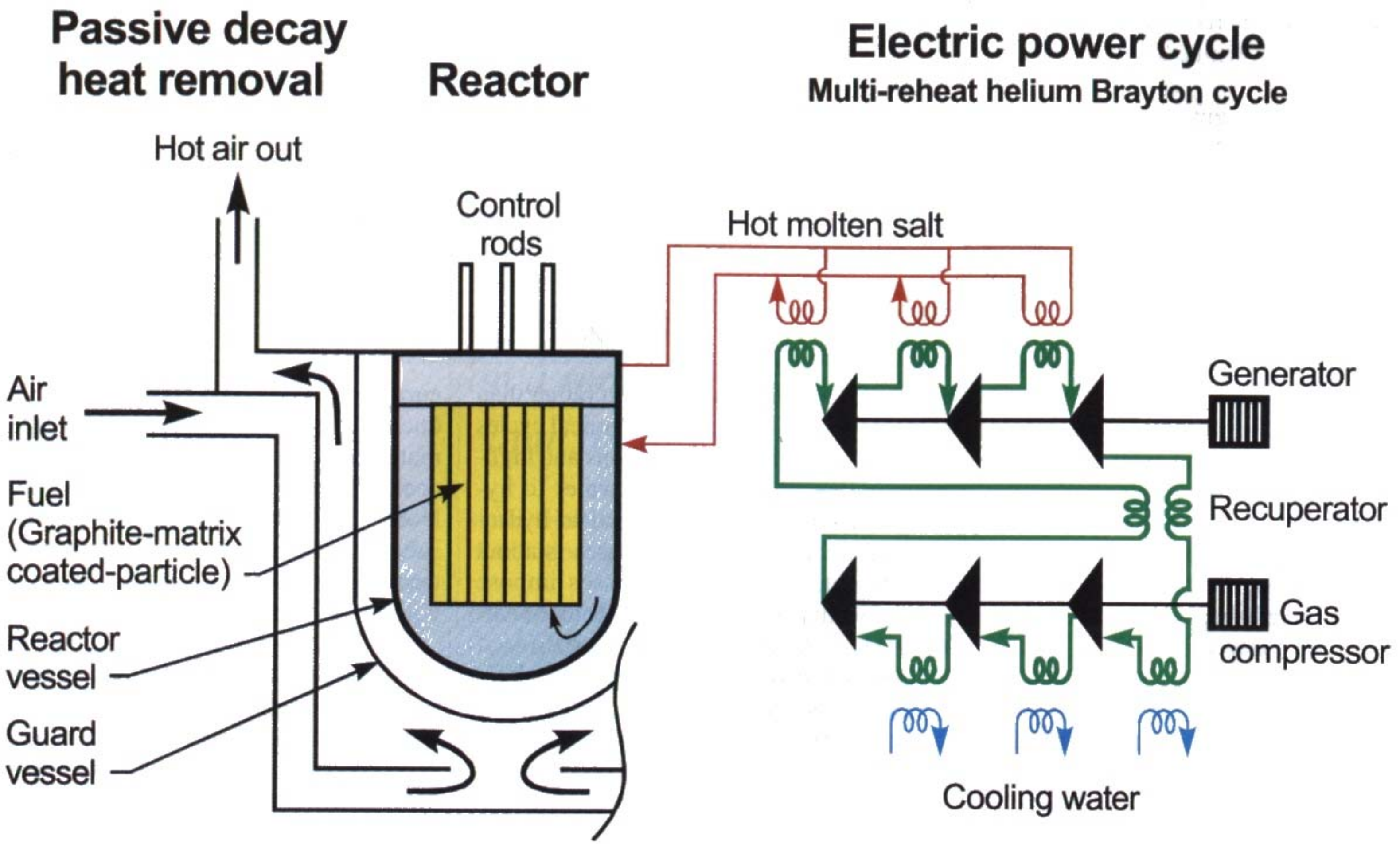
TRISO coated particle



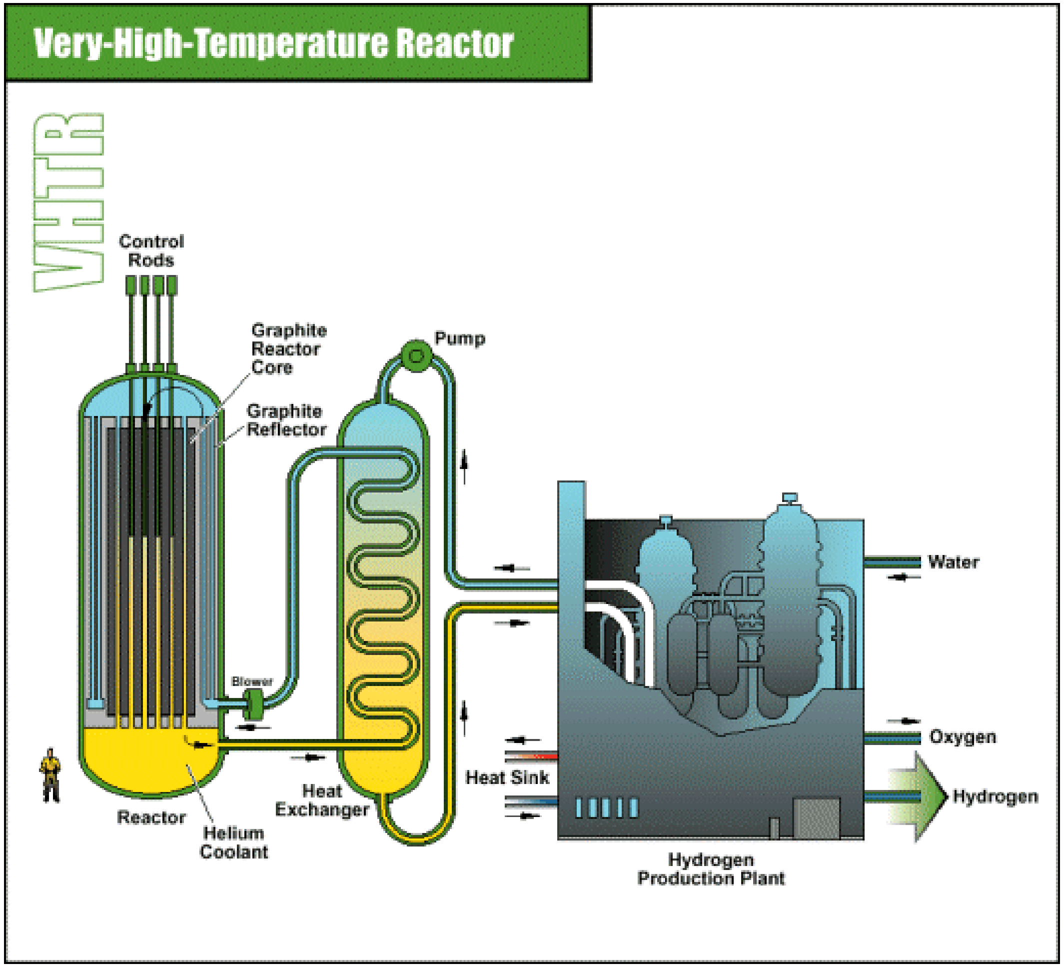
HTR response to Loss of Coolant



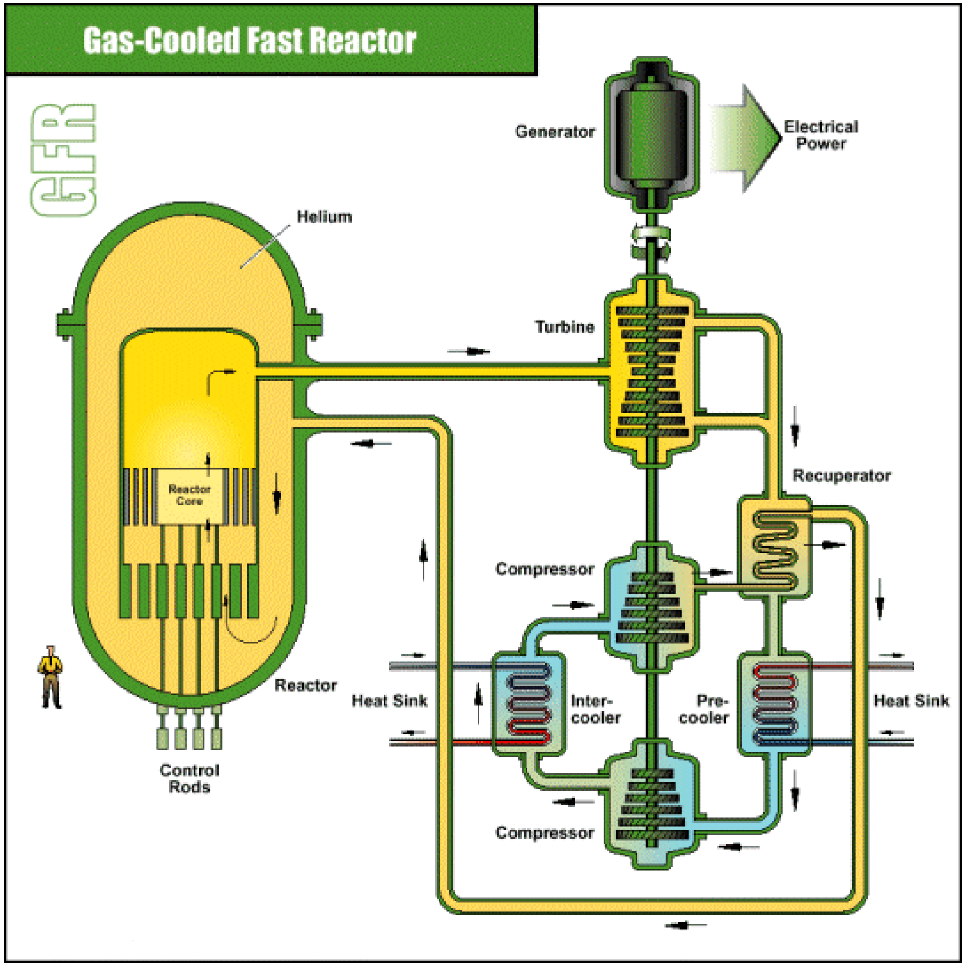
Advanced High Temperature Reactor



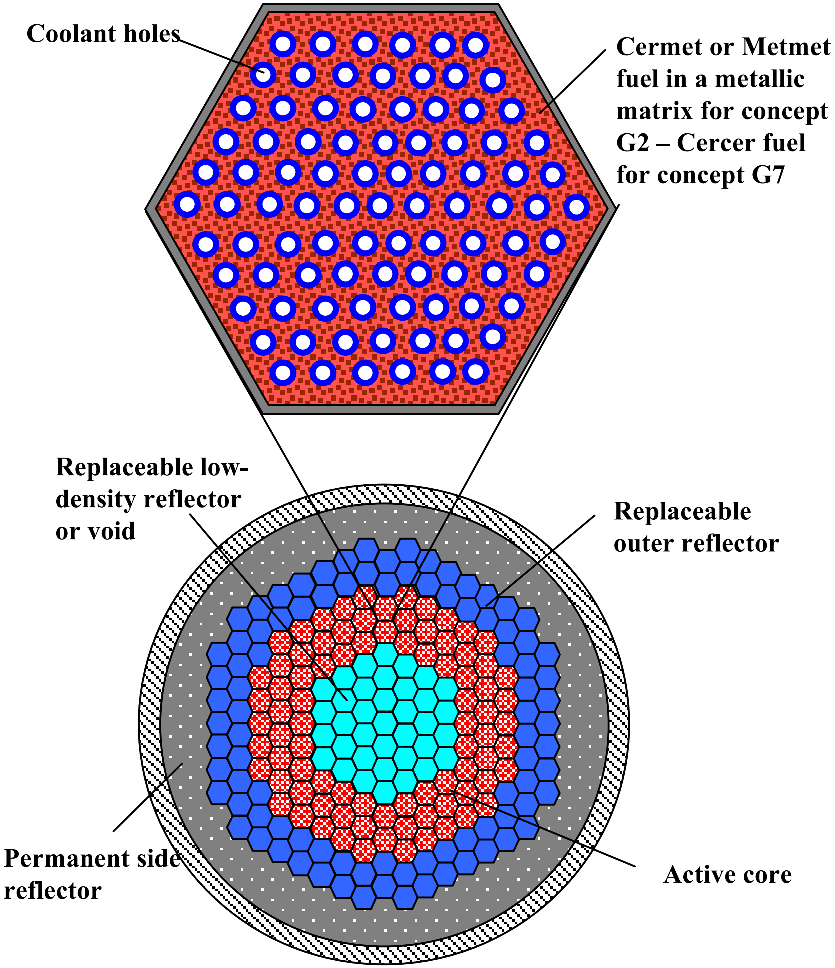
Very-High Temperature Reactor



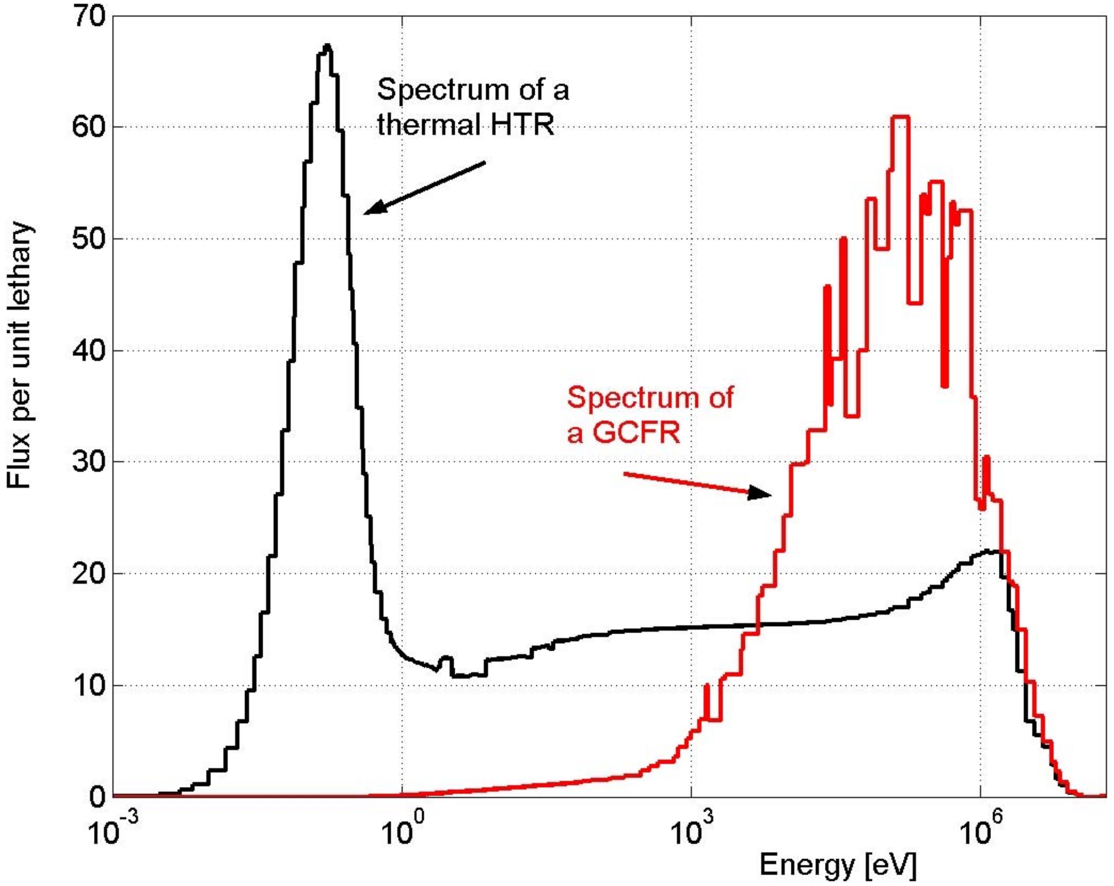
Gas-Cooled Fast Reactor



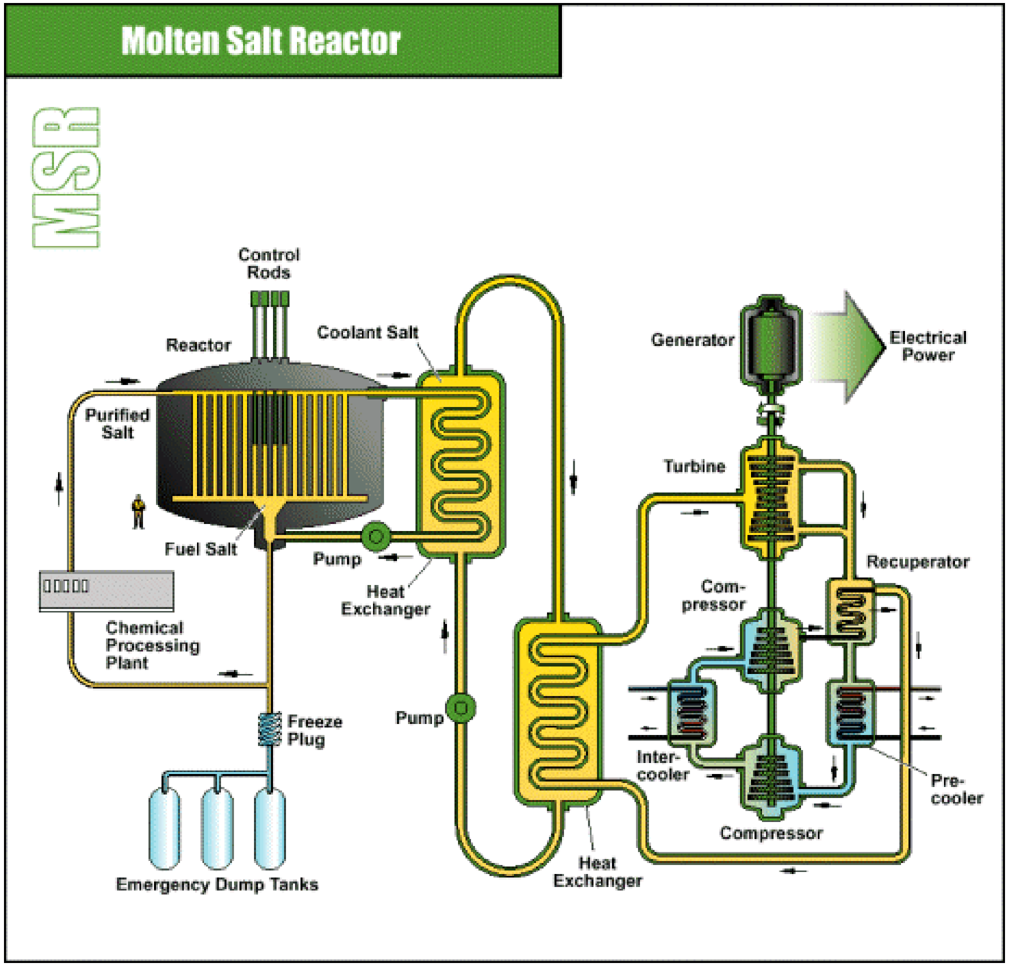
Example GFR Prismatic Fuel



Spectrum thermal/fast reactor

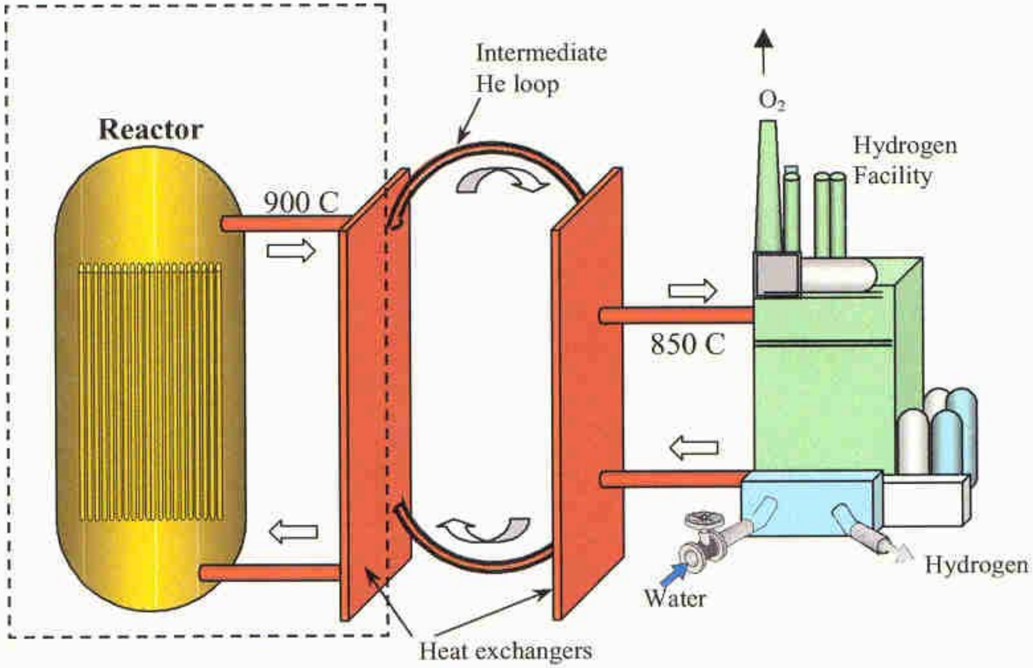


Molten Salt Reactor



Conclusion: sustainable hydrogen

- Nuclear energy is a promising option to produce hydrogen with no emission of greenhouse gases
- Hydrogen production can become a major nuclear energy application



Conclusion: sustainable hydrogen

Short term:

- Introduction of HTR (generation III+)
- Hydrogen production via steam reforming natural gas (or combined production of hydrogen and methanol)

Medium term:

- Introduction of AHTR and VHTR
- Hydrogen production via thermochemical processes

Long term:

- Introduction of GCFR and MSR

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