High Temperature Nuclear Reactors: A Review

Roger Barlow
The University of Huddersfield

International Synthetic Fuels Conference
GITAM, Visakhapatnam, Andhra Pradesh

19th August 2024

The Past

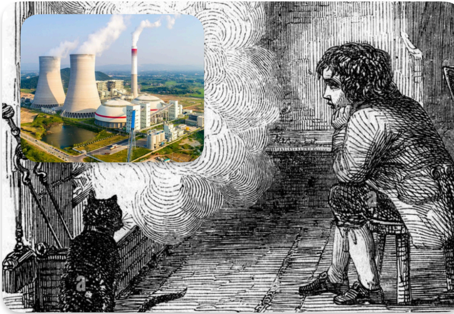
The Industrial Revolution started when the young James Watt noticed the power of the steam generated by his mother's kettle (around 1750)

Steam engines, steam locomotives, steamships – the Age of Steam

The Present

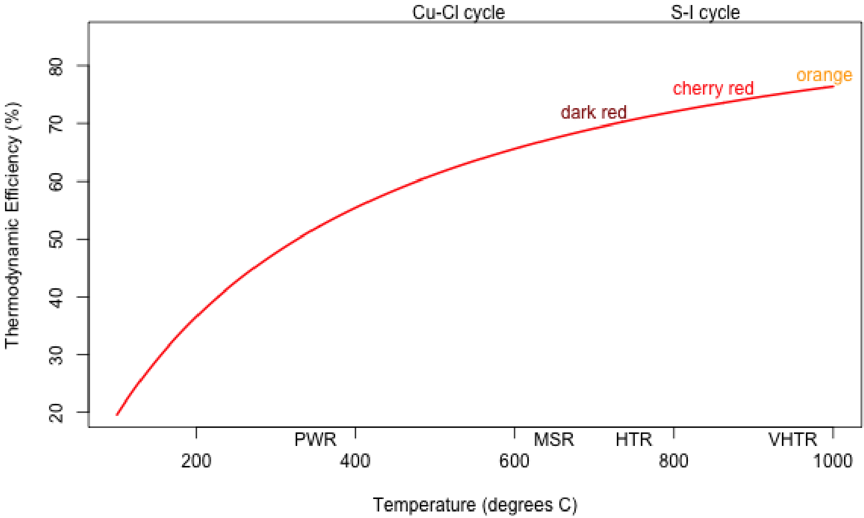
Much of the power generation industry is still living in the Age of Steam

Today's power stations – even nuclear power stations – are essentially steam kettles with a turbine attached



This limits the operating temperature - and high temperatures are good!

Temperature



Reactors

ballpark figures

Status	Type	Moderator	Coolant	Pressure bar	Temperature °C
Commercial	PWR	H_2O	H_2O	155	320
	CANDU	D_2O	D_2O	160	305
	EPR	H_2O	H_2O	155	327
	AP1000	H_2O	H_2O	155	321
	AGR	Graphite	CO_2	40	640
Test	MSR	Graphite	Flourides	~ 1	650
	HTR	Graphite	He	30	750
	HTTR	Graphite	He	40	950
Gen IV	GFR	–	He	90	850
	LFR	–	Pb	~ 1	800
	MSFR	–	Flourides	~ 1	725+
	SCWR	(H_2O)	H_2O	250	625
	SFR	–	Na	~ 1	550
	VHTR	Graphite	He	70	1000

Coolant

Alternatives to water/steam

Gas

Usually helium - chemically inert and small molecular mass makes pumping easier. CO_2 has been used.

Usually under pressure - but not as high pressures as steam.

Liquid

Coolant	Melts	Boils
Sodium	98	883
Na/K	-11	785
Lead	328	1749
Pb/Bi	123	1670
Flouride salts	459	1430

Operate at atmospheric pressure

Maintenance and repair are tricky if coolant solidifies

Metals can be pumped electromagnetically

Energy extracted through heat exchanger - secondary loop used for extracting useful work, avoiding complications of active primary coolant. Flow usually convective, assisted by pumps. Convective flow should be enough to remove decay heat when shut down.

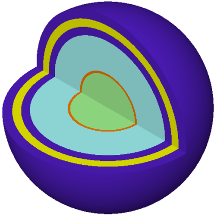
Fuel

Conventional

'Prismatic' Fuel rods

TRISO

'Tristructural Isotropic'
Particles "the size of poppy seeds" have $\mathrm{UO_2}$+carbon centre, coated with graphite and silicon carbide. Particles contain all their fission products so no worries about escapes.
Often formed into 'pebbles'. Go well with gas cooling.

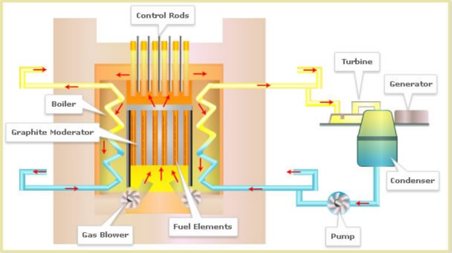


Molten Salt

Uranium and thorium (as flourides) dissolved in salt.

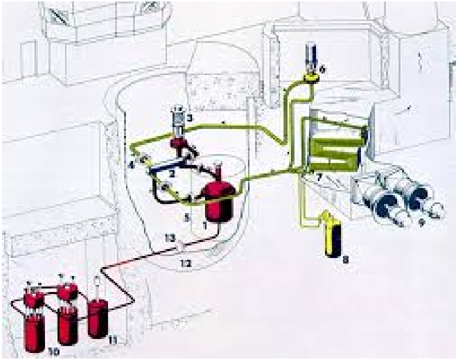
AGR:Advanced Gascooled Reactor

UK design: 1976-2028(?)
640 C outlet temperature - matches coal-fired generators
14 reactors built: 8 still operational
Larger footprint than PWR



Long history of technical and commercial problems
CO_2 coolant reacts with graphite core

MSR: The Molten Salt reactor

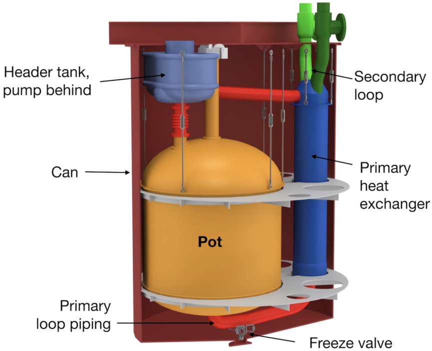


Oak Ridge 1964-69
Ran with 235 U and 233 U
Just a demonstrator
8 MWt : 704 C
$\mathrm{LiFBeF_2ZrF_4UF_4}$
Hastelloy N steel usable up to 871 C

Interest continues, also in MSFR - Molten Salt Fast Reactor
Similar but without graphite

Very stable due to expansion of salt with temperature

MSR reactor: ThorCon



Based on the Oak Ridge MSR experiment
(But uses sodium instead of lithium in the salt)
Heats salt from 565 to 700 C
3000 kg/s pumping, flowing through graphite moderator
250 MWe (per unit)
Can be constructed by conventional shipyard
Planned deployment in Indonesia

Sodium cooled Fast Reactors

PFBR at Kalpakkam, Bay of Bengal
490C, 500 MWe
Being commissioned now
Based on experience with FBTR 13MWe
Emphasis on Pu and $^{233}\mathrm{U}$ production

Previous SFRs at Dounreay (UK) and Superphénix (France) were plagued by problems

Bill Gates' TerraPower Natrium Reactor under construction. 2030?

LFR: Lead-cooled Fast Reactors

Typically 500-600 C. 800 is possible. Lead and LBE (Lead-Bismuth Eutectic)

Used in Sovier nuclear submarines.
Beryllium moderator
Problems due to need to keep coolant molten, and to uneven cooling.

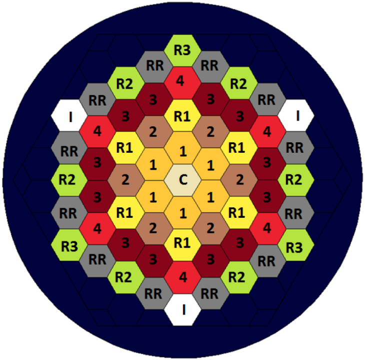
Proposed today for MYRRHA, SCK-CEN, Belgium
ADSR, fast reactor. 100 MWt
Emphasis on burning actinides and on medical isotope production.

Gas cooled: HTR-PM (Tsinghua, China)

after HTR-10 test version
2x250MWt reactors
Pebble-bed TRISO using 6 cm diameter pebbles: 400,000 pebbles per reactor
Commercial, connected to grid and generating 500C steam for residential heating
Outlet temperatue 567 C but safety tests go up to 1600C

HTTR High Temperature Test reactor (Japan)

950 C, 30 MW, 40 bar graphite moderated



(1-4 are fuel rods, C and R1-R3 are control rods, I is instrumentatiuon, RR is reflector)

TRISO fuel packed in hexagonal blocks

Went critical 1998, full power 2004

Plan to test hydrogen producion in 2028

Final thoughts

- We can go beyond steam-kettles and build high temperature reactors . Indeed, we are doing so already
- 600-700 C has many options. 900-1000 C is within range
- A lot of work has been done. There are many proposed designs with eloquent advocates.
- Above 600-700 C, the main problem is the containment vessel and pipes. Corrosion and erosion in steel.
- It isn't easy. Learn from other people's mistakes.