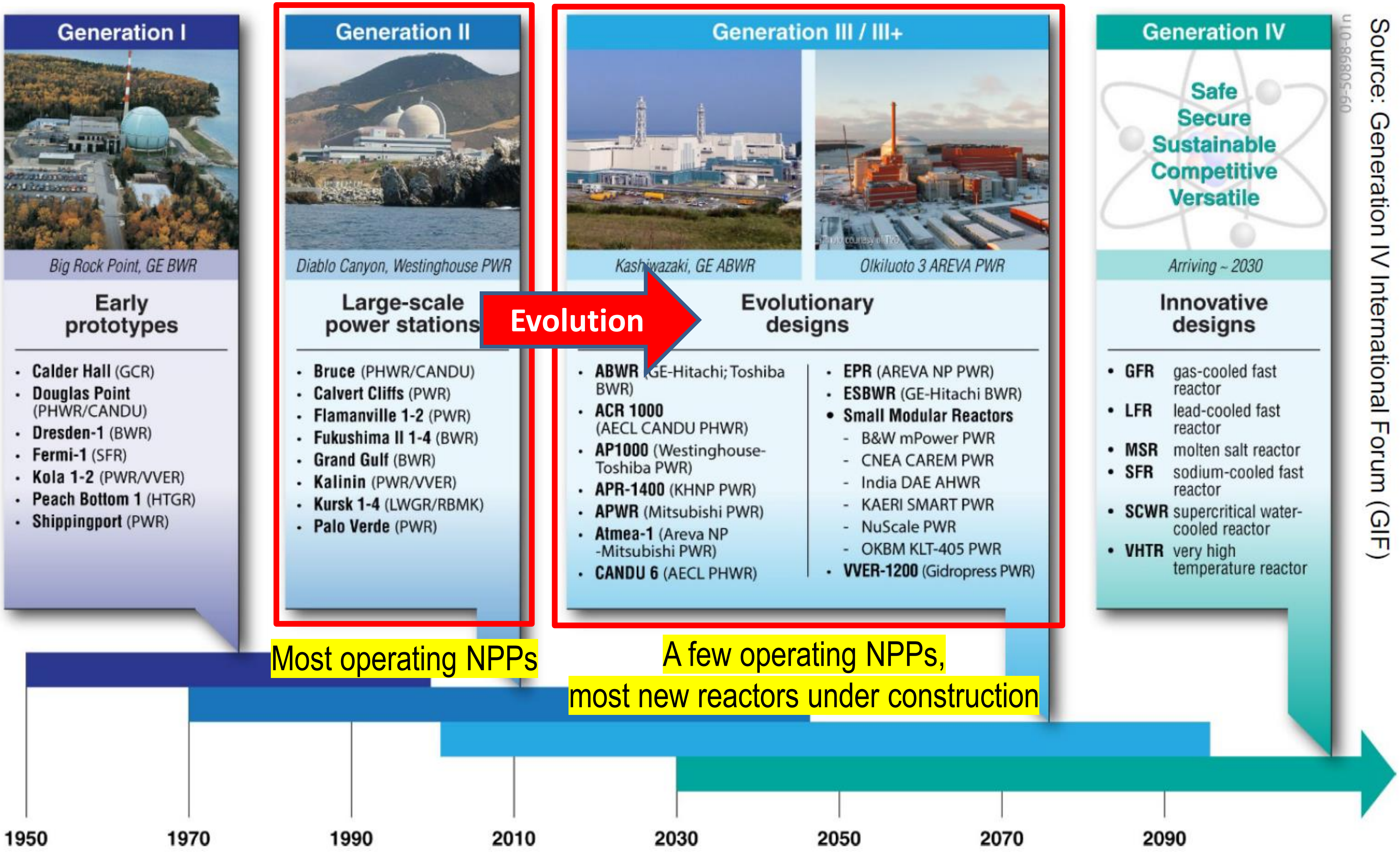
GET1024 / GEC1036 Lecture 12

Future Nuclear Power Plants

- Gen III/III+ Reactors
  - Examples & Safety
- Small Modular Reactors (SMRs)
  - NuScale SMR
- Gen IV Reactors
  - High Temperature Gas-cooled Reactors (HTGRs)
  - Molten Salt Reactors (MSRs)
  - Sodium-cooled Fast Reactors (SFRs)
- Fusion Reactors (briefly)

Generations of Nuclear Power Reactors



Source: Generation IV International Forum (GIF)

Further Improvements to the Safety of NPPs

- Given that risk for a severe accident involving core melt is not negligible (~1 in 10,000 reactor-years) for many of the existing Gen II reactors, new generation of reactors (Gen III/III+) were designed and built to reduce the risk by 10 to 100 times.

- This is done through evolutionary designs that have
  – Higher level of redundancy and diversity
  – Combination of passive and active safety systems
  – Eliminating potential initiating events for core melt

- Efforts have also gone into looking at other designs beyond light water reactors (including some of the abandoned designs of the 1950s) that may be inherently safe – basic physics or chemistry of the systems does not permit any meltdown – instead of safety through designs. These can be seen in some of the Gen IV reactors such as the Molten Salt Reactors and the High Temperature Gas-cooled Reactors.

Gen III / III+ Reactors

- Evolutionary designs from Gen II. May include the following improvements:
  - Significantly enhanced safety systems, including additional passive safety systems.
  - Lower core damage frequency, CDF, (<10^{-5} instead of 10^{-4} per reactor-year – some designs claim much lower CDF.)
  - Longer operational life (60 years instead of 40 years)
  - Higher performance, e.g., in fuel efficiency, longer refueling cycle, etc.
  - Lower cost of construction and maintenance (?) – simplified design, standardized parts

- A number of designs for both PWRs, BWRs and PHWRs have been proposed – not all have been built.

- Currently there are a few operating reactors are of Gen III/III+, including ABWR, APR-1400, AP1000, EPR, HPR1000, ACPR1000 and VVER1200. All except ABWR are PWRs.

- Most of the reactors under construction now are of this generation.

Existing and Under Construction Gen III/III+ NPPs

HPR1000 (Hualong One, PWR)

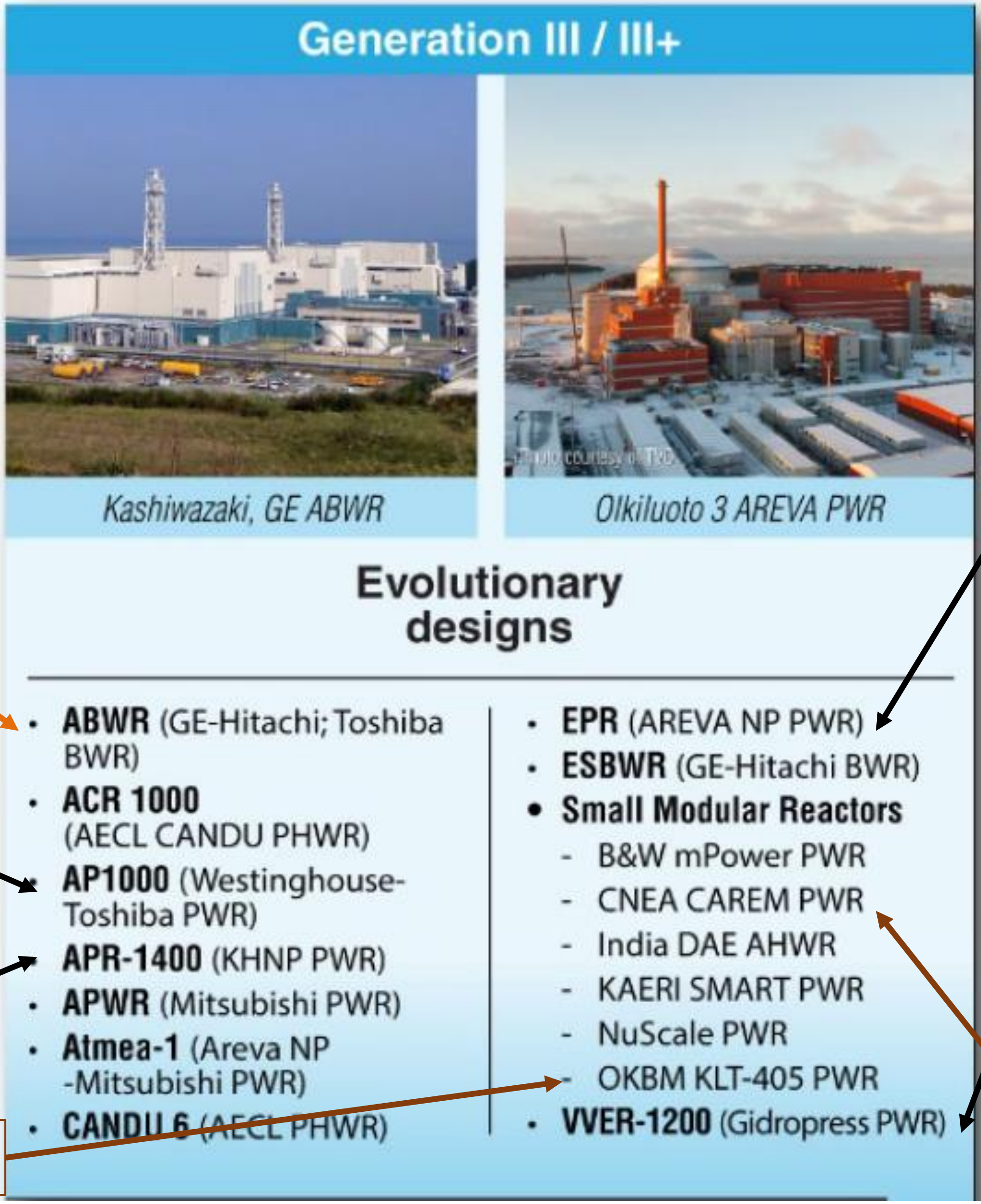
Fuqing, China (2, 2020/2022)
Fangchenggang, China (2, UC)
Zhangzhou, China (2, UC)
Changjiang, China (2, UC)
Taipingling, China (2, UC)
Sanaocun, China (2, UC)
KANUPP, Pakistan (1, critical)

Kashiwazaki, Japan (2, 1996)
Shika, Japan (1, 2005)
Hamaoka, Japan (1, 2004)

Haiyang, China (2, 2018)
Sanmen, China (2, 2018/19)
Vogtle, US (2, UC)

Shin-Hanul, Korea (2, UC)
Shin-Kori, Korea (4, 2016/19/UC)
Barakah, UAE (4, 2020/21/ UC)

Akademik Lomonosov, Russia, 2, 2019)



ACPR1000 (PWR)

Yangjiang, China (2, 2018/19)
Hongyanhe, China (2, 2021, UC)
KANUPP, Pakistan (1, 2021)

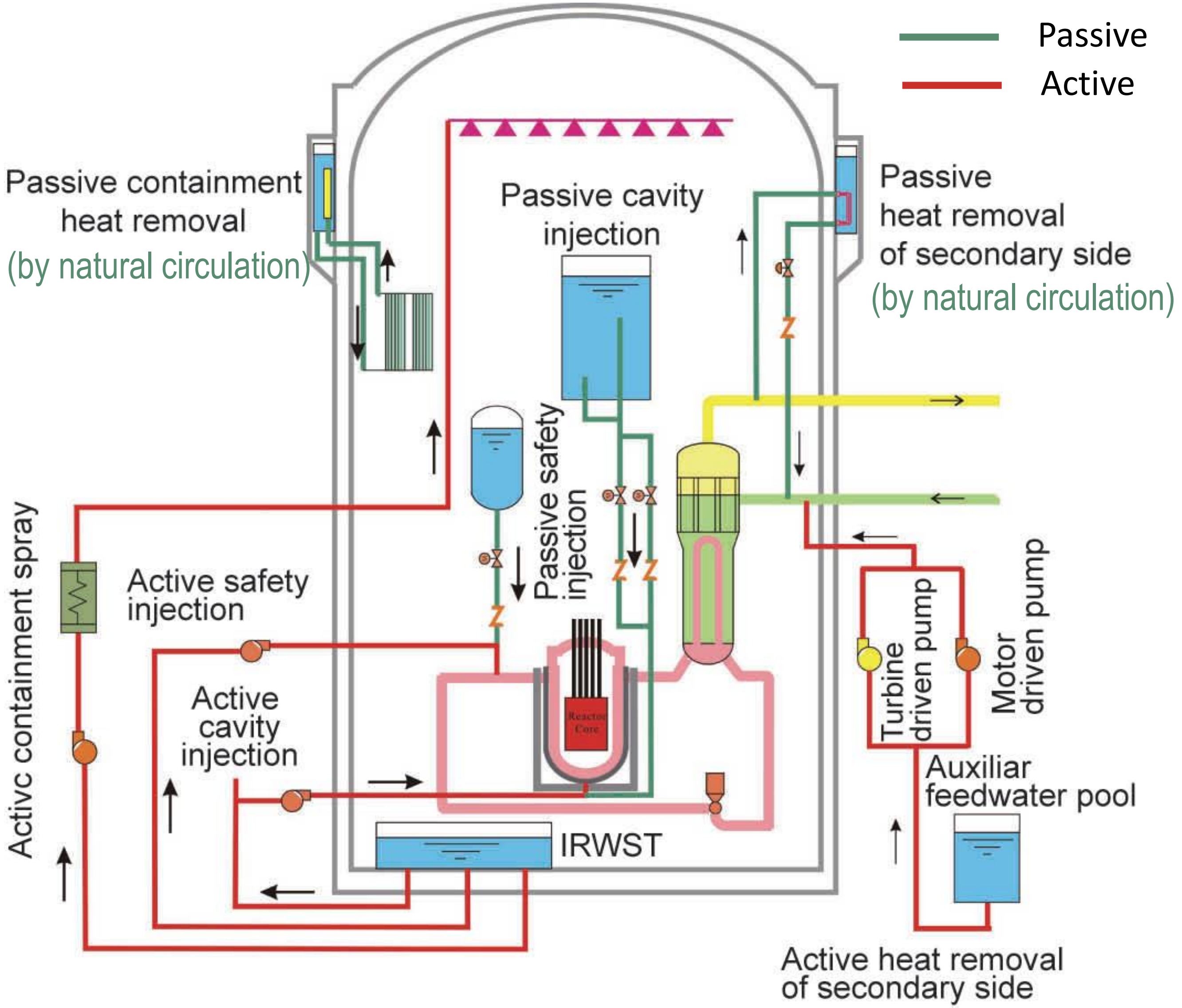
Olkiluoto, Finland (1, UC)
Flamanville, France (1, UC)
Taishan, China (2, 2018/19)
Hinkley Point, UK (2, UC)

Leningrad, Russia (2, 2018/20)
Baltic, Russia (1, UC)
Novovoronezh, Russia (2, 2016/19)
Kursk, Russia (2, UC) *VVER-TOI*
Belarusian, Belarus (2, 2020/UC)
Akkuyu. Turkey (3, UC)
Rooppur, Bangadesh (2, UC)
Tianwan, China (1, UC)
Xudabu, China (1, UC)
~~Ninh Thuan, Vietnam (2)~~

Carem25, Argentina, 1, UC)

Example: Safety Systems in HPR1000 (Hualong One)

- Most systems have both active and passive trains.
- IRWST – inside containment
- Cavity injection – cool reactor vessel from outside – in vessel retention strategy.
- Passive containment & secondary side heat removal – by natural circulation and can last for 72 hours.
- 33 passive autocatalytic recombiners (to reduce hydrogen in containment)
- Double-wall containment.
- Diversity of emergency power



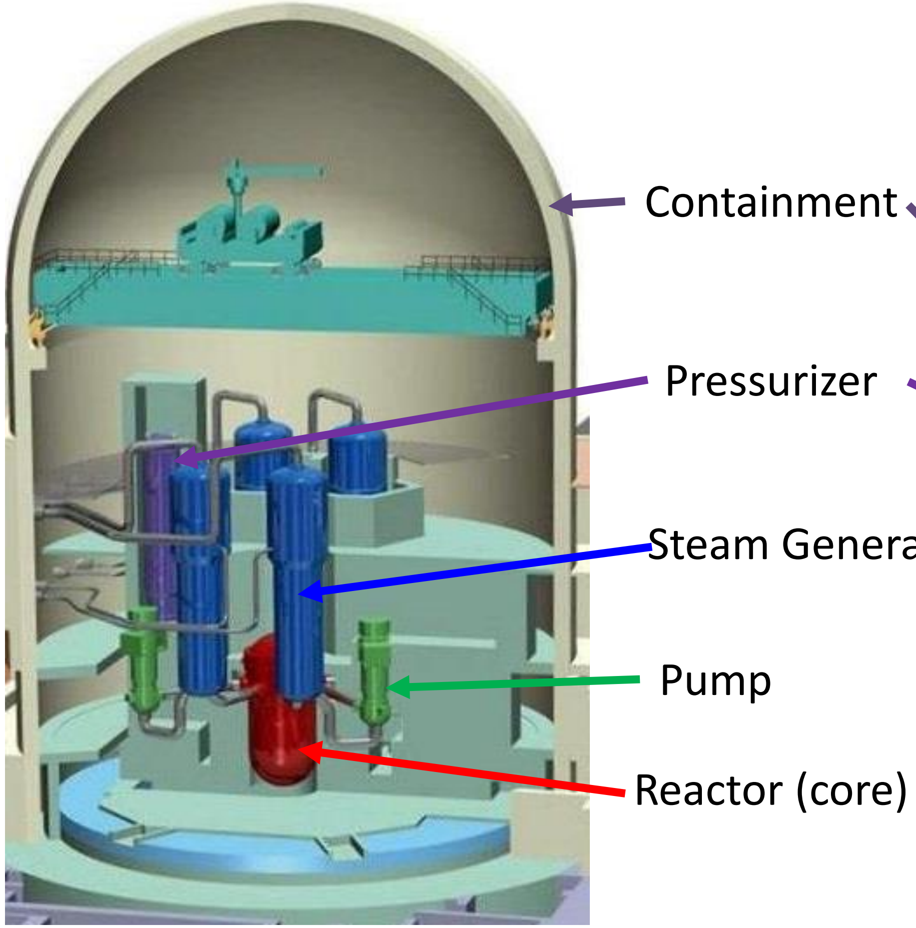
IRWST: In-Containment Refueling Water Storage Tank

Small Modular Reactors (SMR)

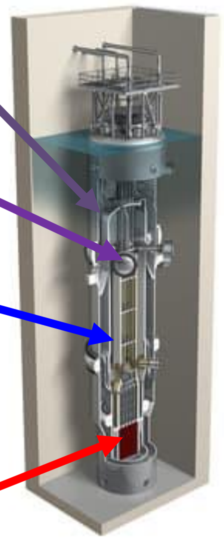
- Small (< 300 MW_e) modular (assembled in factory as a module to be brought to transported to site) reactors are being seriously considered in many countries.
- Attractiveness of SMRs
  - Safety – Lower decay heat per reactor. Passive safety system, e.g., using natural convection, can remove decay heat efficiently to reduce chance of core melt.
  - Cost – initial cost is much less – and so more incentive for investors. Construction time is also greatly reduced. (Note: actual cost per kWh may be higher.)
  - More reactors can be connected together or added according to demand. One reactor can be refuelled, decommissioned, etc. with the rest operating.
  - Construction period – shorter due to pre-fabrication of the modules in factory and assembled on site.
  - May be more hands-off – less technical expertise needed to run the system – good for remote area which also needs lower power.
- Many systems were proposed using light water reactor technologies, e.g., NuScale (US, 12 x 77 MWe), KLT-40S (Russia, floating, 2 x 35 MWe), ACP100 (China, 100 MWe), NUWARD (France, 2 x 170 MWe), SMART (Korea, 100 MWe), RITM-200N (Russia, 55 MWe). The designs are more mature and tested.
- Other technologies, e.g., Toshiba 4S (sodium cooled, Japan, 10 MWe), IMSR (molten salt, Canada, 33 – 291 MWe), etc. The HTR-PM (China, 2 x 105 MWe) may also be considered as an SMR.

PWR → Integral PWR (iPWR) SMR

- Many new designs of SMR are known as Integral PWR or iPWR which integrates the steam generator with primary system (with or without pump)



Conventional Large Pressurized Water Reactor (PWR)



Small Modular Reactor (e.g., NuScale iPWR)

Notable SMR Design

ACP100 showcased

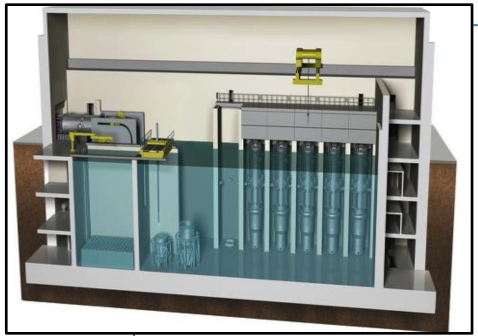
ACP100 (China, 2 x 100 MWe)

- ACP100 has started construction in July 2021 at Changjiang NPP in Hainan province;
- Estimated to take **60 months** to complete

Akademik Lomonosov **docked.**

KLT-40S (Russia, 2 x 35 MWe)

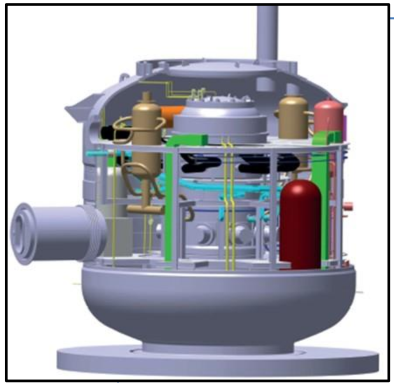
- Towed and reached final destination in Sep 2019.
- Connected to the grid in Dec. 2019, commercial operation at the end of May 2020
- Expected to be one-of-a-kind.



NuScale reactor modules.

NuScale (USA, 12 x 50* / 77 MWe)

- * Received Standard Design Approval issued by U.S.NRC in Sept. 2020.
- NRC agreed that the **SMR does not need backup power** and may have a **smaller emergency planning zone**.
- UAMPS will build its first plant at Idaho National Lab.



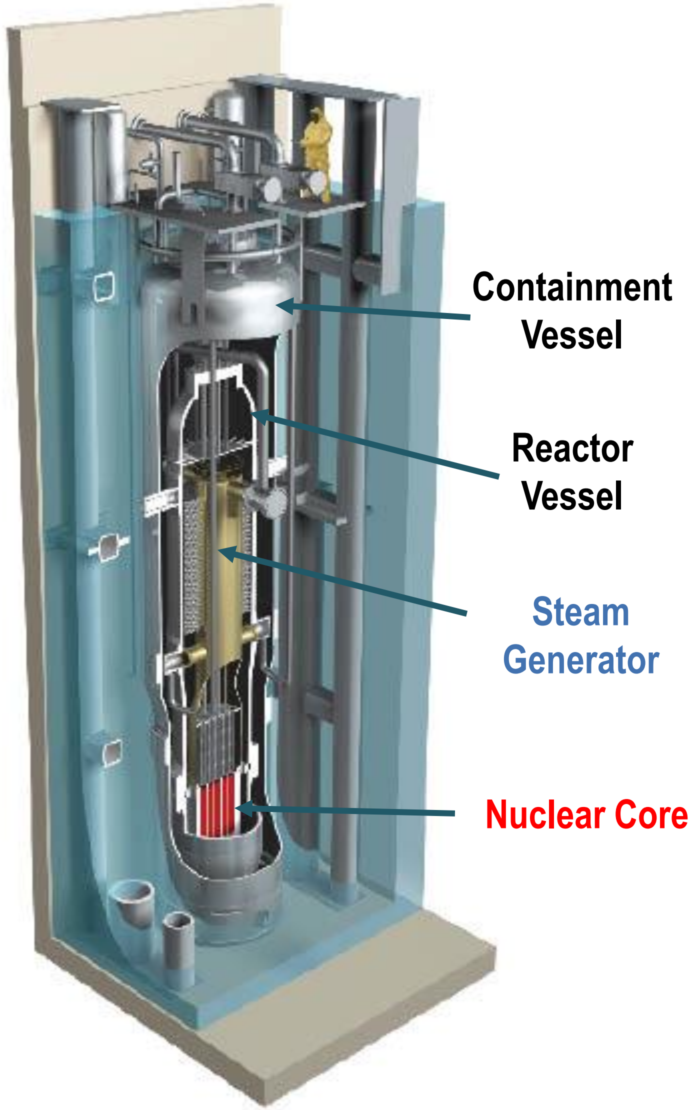
NUWARD reactor module

NUWARD (France, 2 x 170 MWe)

- Developed by EDF, CEA, etc. Close to completing conceptual design.
- First Unit Construction by 2030.
- Strong interest in Europe – joint review by ASN, STUK, SUJB.

- Based on light water technology – similar to most currently operating reactors.
- Other notable designs include CAREM (Argentina – under construction in 2014, expected to start operation in 2023), RITM-200 (Russian, both land and marine-based), NUWARD (French), etc.

NuScale SMR

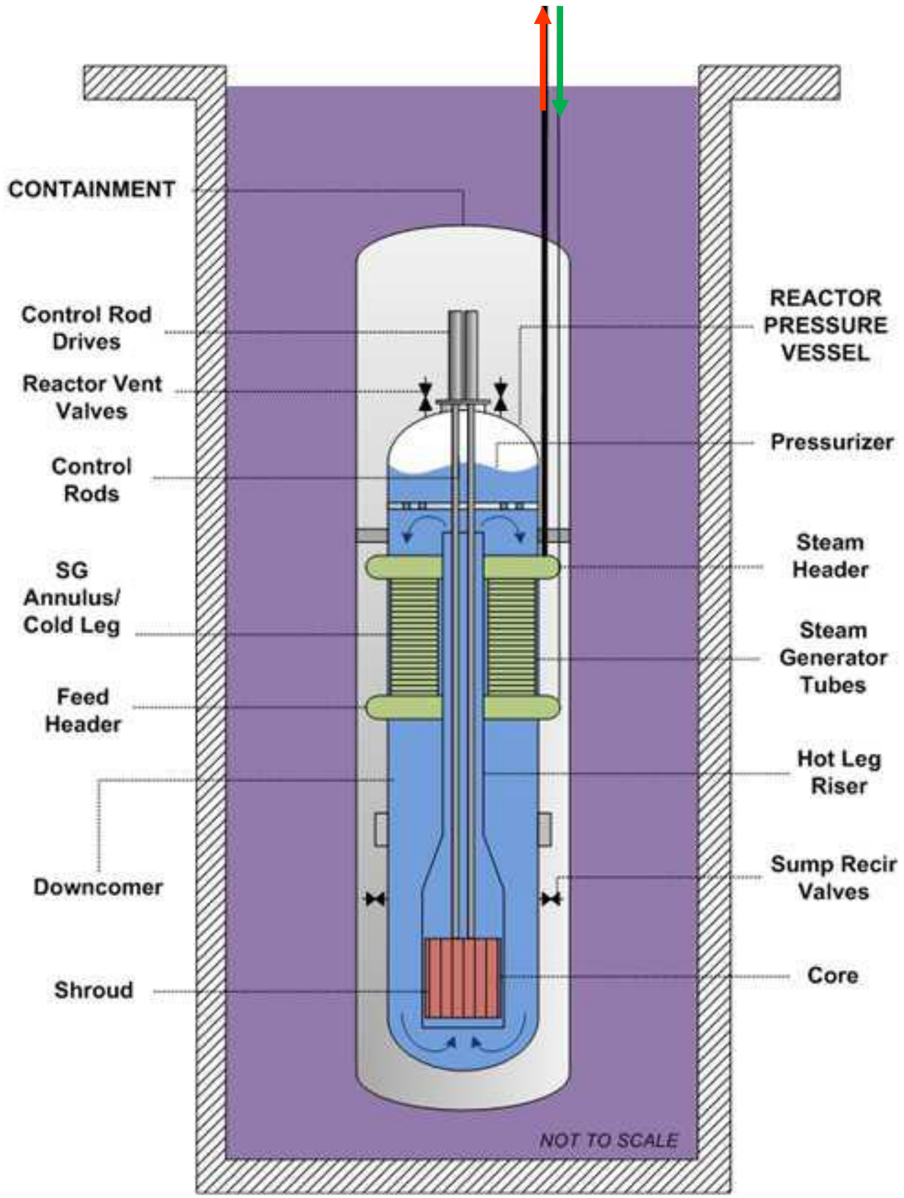


- Reactor vessel – 2.7 m diameter by 20 m
- Containment vessel – 4.5 m diameter by 25 m.
- Light water reactor technology.
- 50 MW_e of electricity (160 MW_t thermal) each and require refueling with less than 4.95 percent enriched uranium fuel every two years.
- Active core height = 2.0 m.
- Pressure in reactor vessel = 12.76 MPa (129 atm)
- Passive cooling system – natural circulation – heated water from core rises, passes over steam generator – cooled and falls down (by gravity).
- Pre-fabricated, delivered by railcar, barge or special trucks and assembled on-site. About 650 tonnes for each unit.

http://www.powermag.com/nuscale-puts-single-minded-focus-on-small-modular-reactor

NuScale SMR – Normal Operation

- Water heated by core rises in the hot leg riser.
- Steam generator – helical tubes around the riser. Water in SG tube heated up and turns to steam.
- Water in hot leg riser cooled and returns to base of vessel via the downcomer at side.
- Water moves through natural circulation – no pump, valves or pipes.
- Pressure control by pressurizer (heater).
- Control rods from top as in PWR.
- Space between containment and vessel evacuated – thermal insulation, less corrosion, no oxygen for hydrogen explosion in accident – no need for hydrogen combiner.



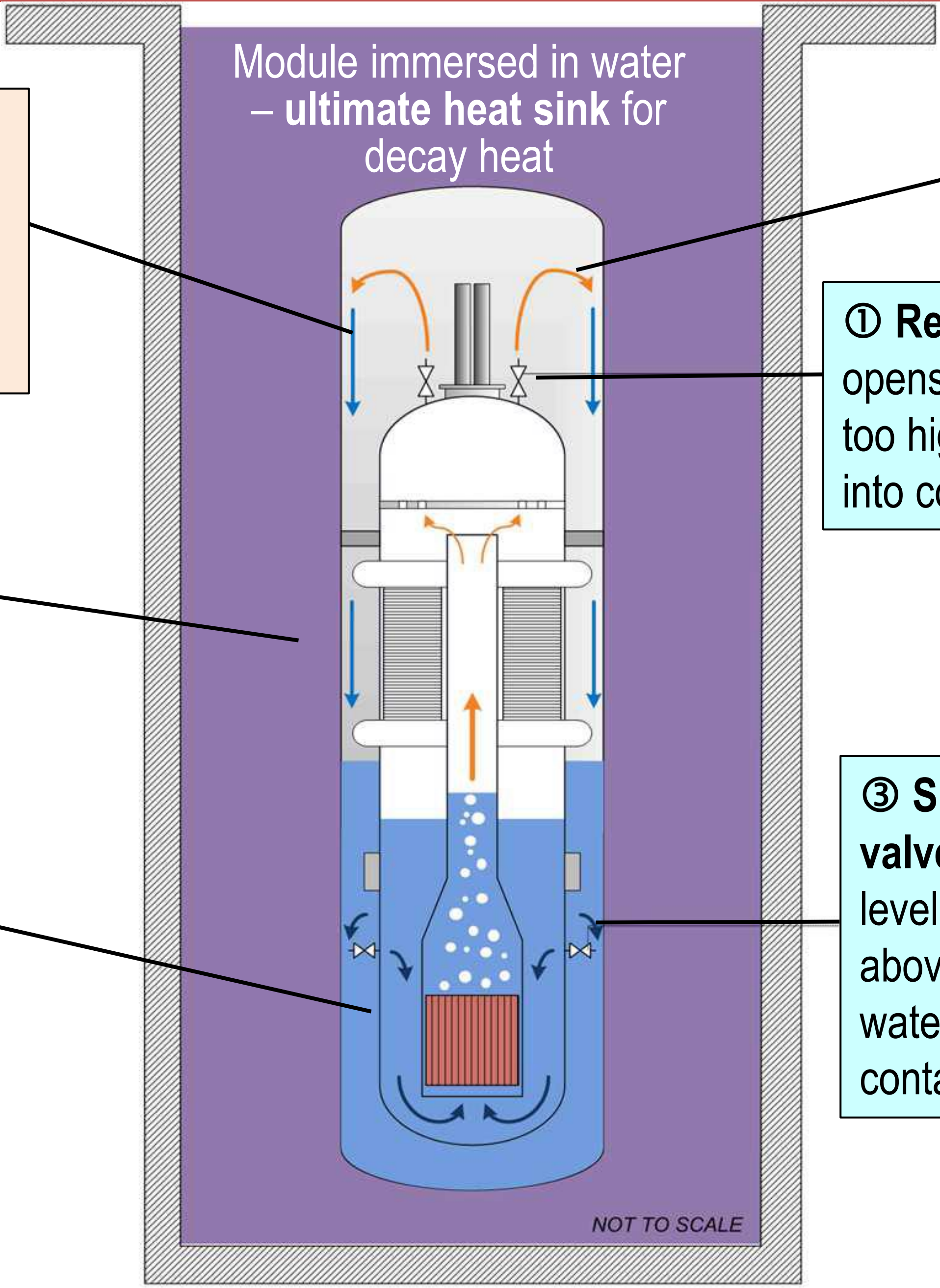
http://www.powermag.com/nuscale-puts-single-minded-focus-on-small-modular-reactor

NuScale SMR – Emergency

Containment can withstand up to 5.5 MPa (56 atm) – will not break in design basis accidents.

Enough water in ultimate heat sink to last for 30 days when air cooling is adequate to remove the decay heat.

Water will not be lost from module and core will always remain covered – **core will not melt**.



② Steam in containment will condense (cooled by water outside containment) and flows down

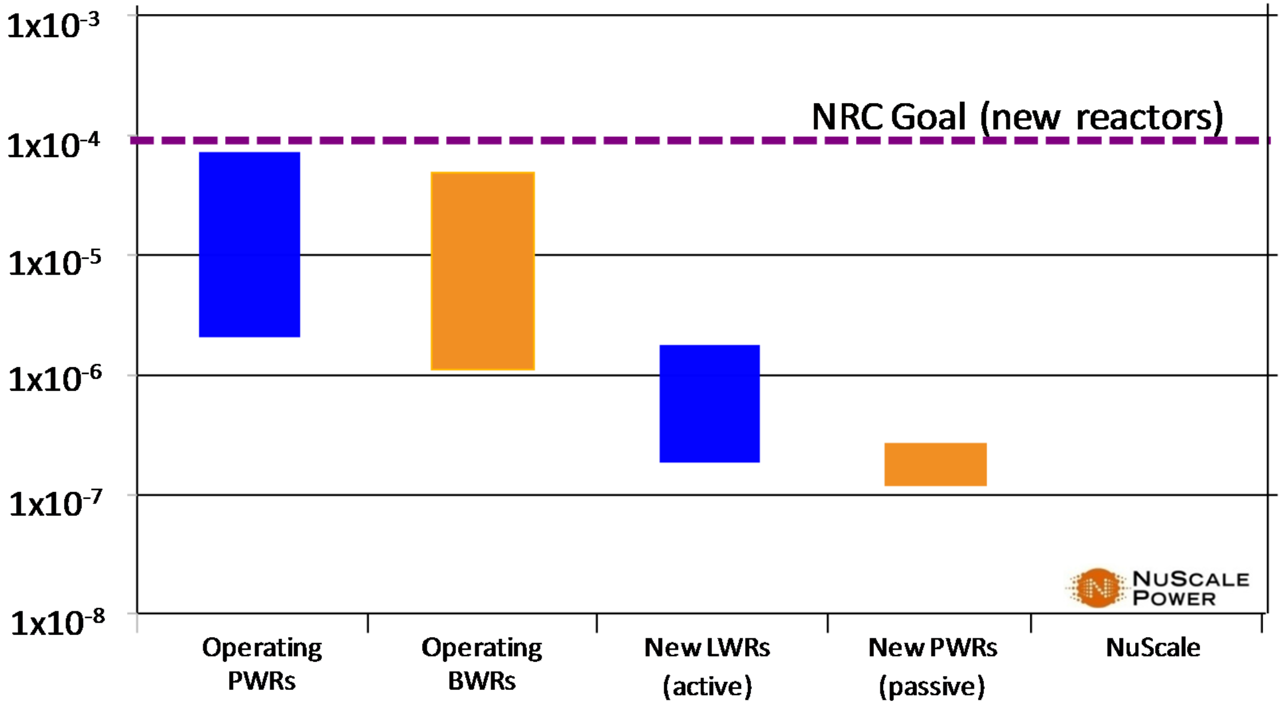
① **Reactor vent valve** opens if pressure in vessel is too high – steam will be let into containment

③ **Sump recirculation valves** will open if water level in containment rises above them. Allow mixing of water in vessel and containment.

http://www.powermag.com/nuscale-puts-single-minded-focus-on-small-modular-reactor

NuScale SMR – Safety Consideration

- NuScale estimated that the SMR core damage frequency to be very low (way below 10^{-7} per reactor year).
- Integral design – no pipe, pump, valve – no such accidents.
- Lower decay heat and FPs per module
- Below grade (ground) level for module
- Long-term passive cooling possible – no Fukushima type of accidents



- No uncovering of core for any foreseeable design basis accident.
- More layers of physical barriers between fission products and environment.

NuScale SMR – Safety Consideration

- 12 modules arranged in two rows, giving 920 MW_e (shown on left is one row with one spare slot for maintenance or storage of spare module).
- The reactor and containment vessel operate inside a water-filled reactor pool built below grade. This provides unlimited period of stable cooling in emergency.
- NuScale claimed that if all decay heat is dissipated in the reactor pool, it will boil over time. Volume of water will decrease but the decay heat will ultimately reduce to below 400 kW per module and can be air-cooled before modules are uncovered with water.

Physical barriers to release of radioactivity to environment: (1) oxide fuel pellet and cladding, (2) reactor vessel, (3) containment vessel, (4) reactor pool, (5) underground stainless steel–lined concrete pool walls and floor.

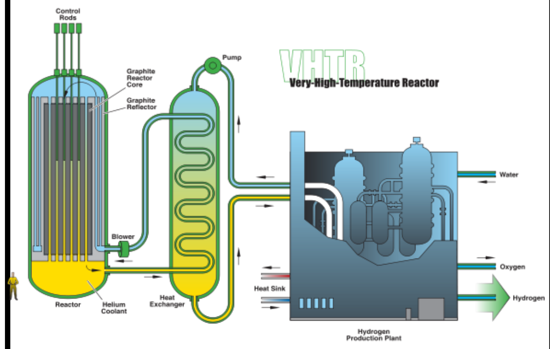
http://www.powermag.com/nuscale-puts-single-minded-focus-on-small-modular-reactor

NuScale SMR – Progress Towards Deployment

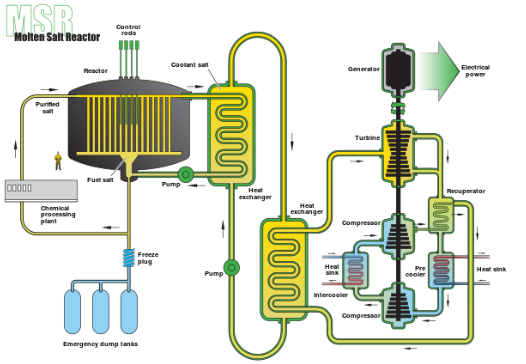
- NuScale submitted its application (for the configuration of 50 MWe per module) to US Nuclear Regulatory Commission (NRC) for the SMR Design Certification in Dec 2016. Actual review started in March 2017. (Only SMR on Design Certification Application.)
- In Jan 2018, NRC concluded that the design is safe enough that it does not require a safety-related electrical backup power (Class 1E) which is currently required for all US nuclear power plants.
- Emergency Planning Zone may be smaller than traditional NPPs.
- Received Standard Design Approval issued by US NRC in Sep 2020.
- First customer is expected to be Utah Associated Municipal Power Systems (UAMPS) and *targeted for commercial operation 2026(?) at site near Idaho Falls*.

Generation IV Reactors

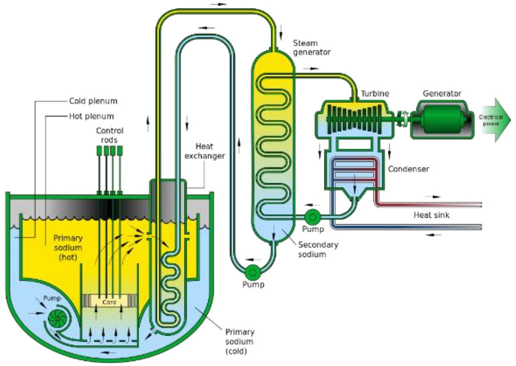
Very High Temperature Reactor



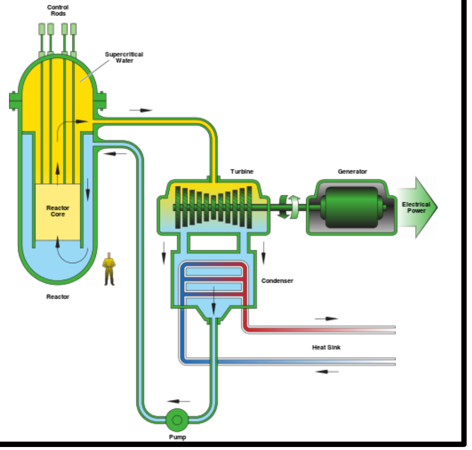
Molten Salt Reactor



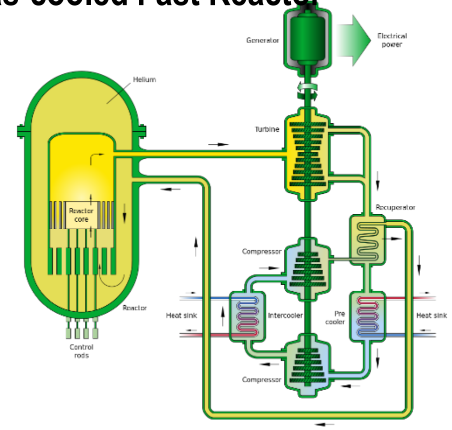
Sodium-Cooled Fast Reactor



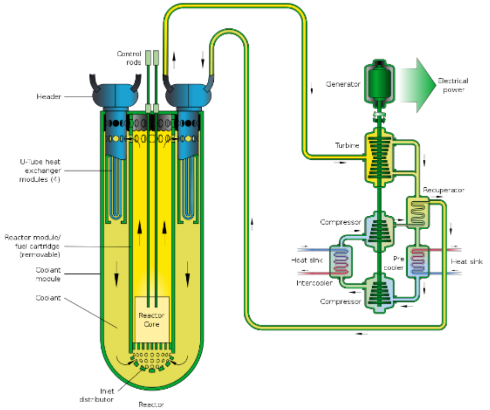
Supercritical Water-Cooled Reactor



Gas-cooled Fast Reactor



Lead-Cooled Fast Reactor



- Generation IV design will use fuel more efficiently, reduce waste production, be economically competitive, and meet stringent standards of safety & proliferation resistance.
- 100 international experts evaluated 130 reactor concepts before GIF (Gen IV International Forum) selected six reactor technologies (see left) for further research and development.
- To be demonstrated in next decade and deployed commercially in 2030s.

https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

Generation IV Reactors

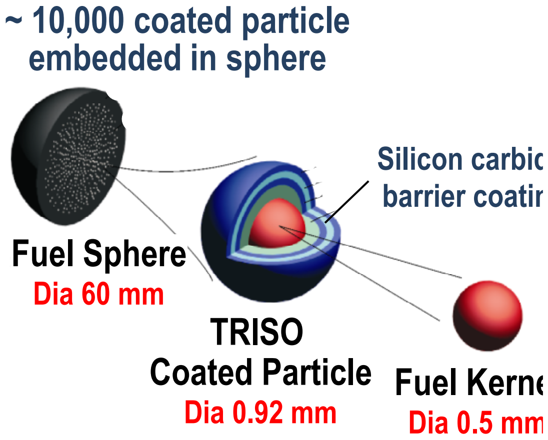
Types	Neutron Spectrum	Coolant	Temp (°C)	Pressure	Fuel	Fuel Cycle	Size (MW_e)	Uses
Gas-cooled fast reactor	Fast	Helium	850	High	U-238	Closed	288	Electricity & H_2
Lead-cooled fast reactor	Fast	Pb-Bi	550 – 800	Low	U238	Closed	150, 300-400, 1200	Electricity & H_2
Sodium-cooled reactor	Fast	Sodium	500	Low	U-238 & MOX	Closed	150 – 1500	Electricity
Molten Salt Reactors	Epithermal	Fluoride salts	700 – 800	Low	UF in salt	Closed	1000	Electricity & H_2
Supercritical water-cooled reactor	Thermal or fast	Water	510 - 550	Very high	UO_2	Open or closed	1500	Electricity
Very High Temperature Reactor	Thermal	Helium	1000	High	UO_2	Open	250	Electricity & H_2

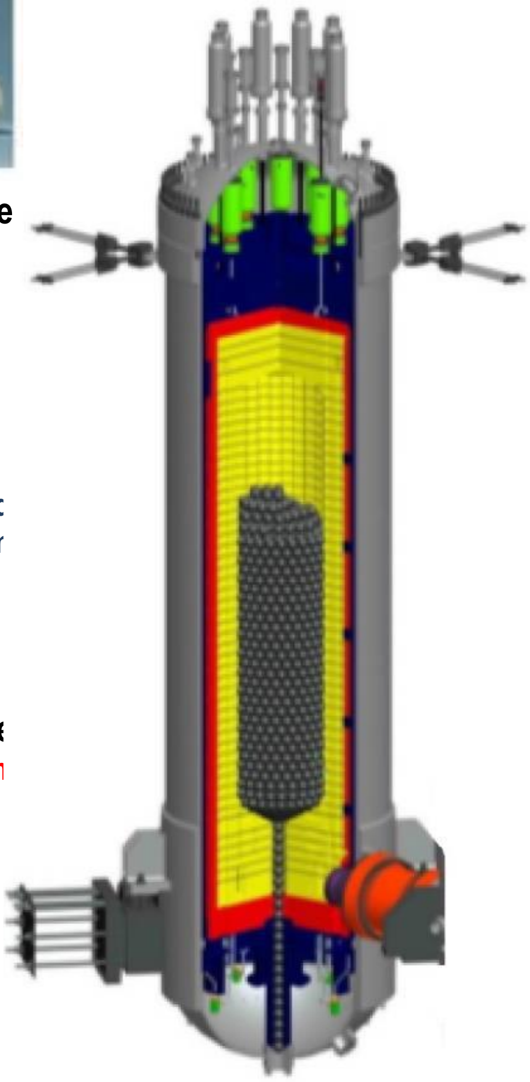
https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

Generation IV Reactors

- TRISO-coated particles (~1 mm dia) - three layers of coating (TRISO-coated) around UO_2 fuel kernel.
- Silicon carbide barrier coating can withstand very high temperatures (> 1,600°C)
- About 10,000 particles in one pebble.
- Fuel consists of 100,000s of billiard ball-sized “pebbles”.
- Operate at high output temperature (~800°C – 1000°C)
  - Higher efficiency in electricity production
  - allows other applications, e.g., desalination, hydrogen production, etc.
- Continuous operation as pebbles are cycled through and spent fuels are not put back.
- Demonstrated to be “walk-away” safe – reactor shuts down safely without operators’ action.
- No active cooling and hence no backup power required for safe shutdown

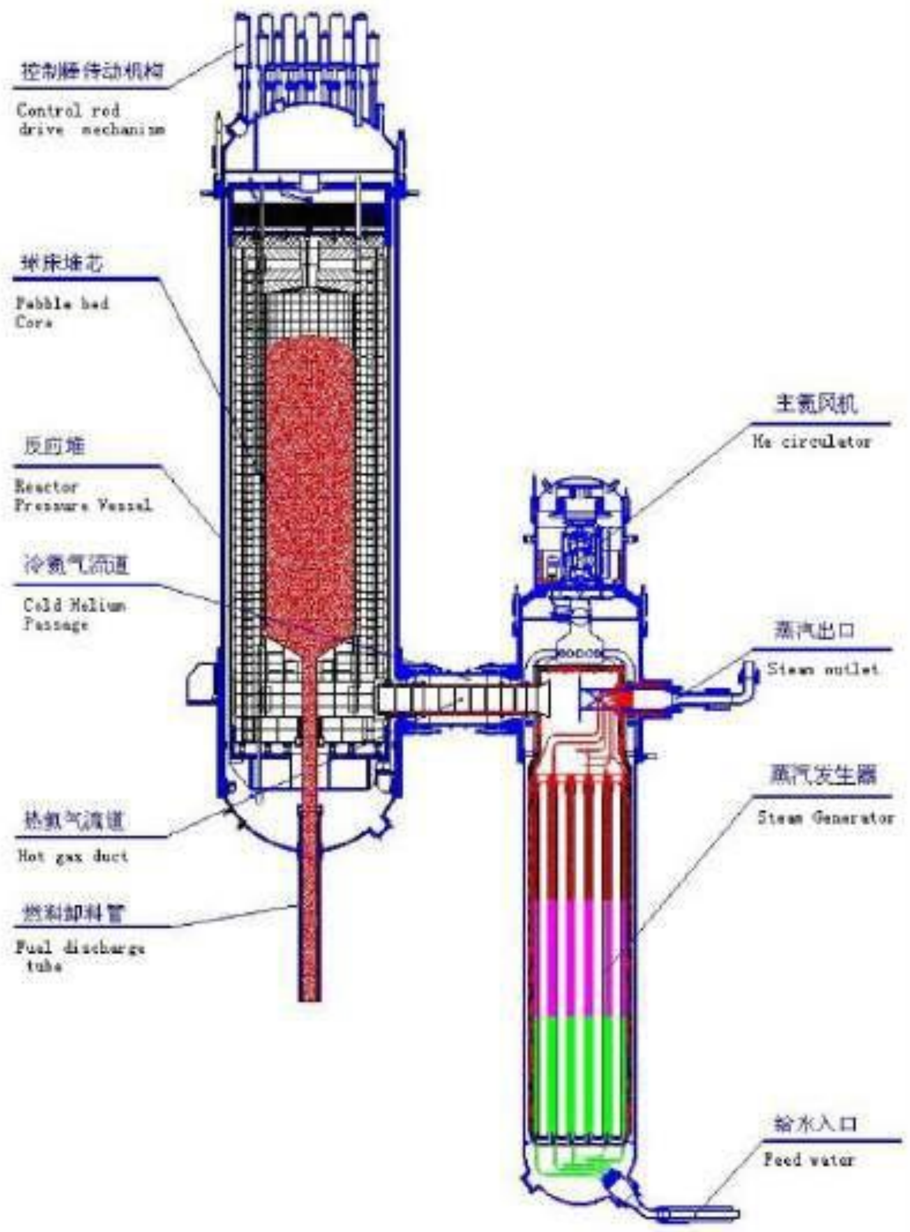
Fuel spheres form a pebble bed in reactor vessel





HTR-PM – Some Characteristics

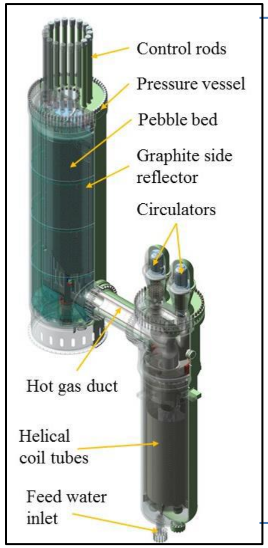
Parameter	Value
Technology developer, country	INET Tsinghua University, China
Reactor type	Modular pebble bed HTGR
Coolant / moderator	Helium / graphite
Thermal / electrical capacity	2x250 MW(t) / 210 WM(e)
Primary circulation	Forced circulation
System pressure	7 MPa
Core inlet/exit temperatures	250°C / 750°C
Fuel type/assembly array	Spherical elements with coated particle fuel
Number of fuel spheres	420,000 (in each reactor module)
Fuel enrichment	8.5%
Fuel burnup (GWd/ton)	90
Fuel cycle (months)	On-line refueling
Main reactivity control	Control rod insertion
Engineered safety systems	Combined active and passive
Design life (years)	40
RPV height/diameter (m)	25 m / 5.7 m (inner)
Seismic design	0.2 (g)
Distinguishing features	Inherent safety, no need for offsite emergency measures
Design status	One reactor connected to grid in Dec 2021



High Temperature Reactor – Development & Prospects

HTR-PM (China, 2 x 105 MWe)

- Criticality were achieved at the two reactors on 12 Sep and 10 Nov 2021
- One reactor connected to grid on 20 Dec 2021 and began producing power.
- The dual-reactor unit is expected to be fully operational in mid-2022.



XE-100 (USA, 82.5 MWe each)

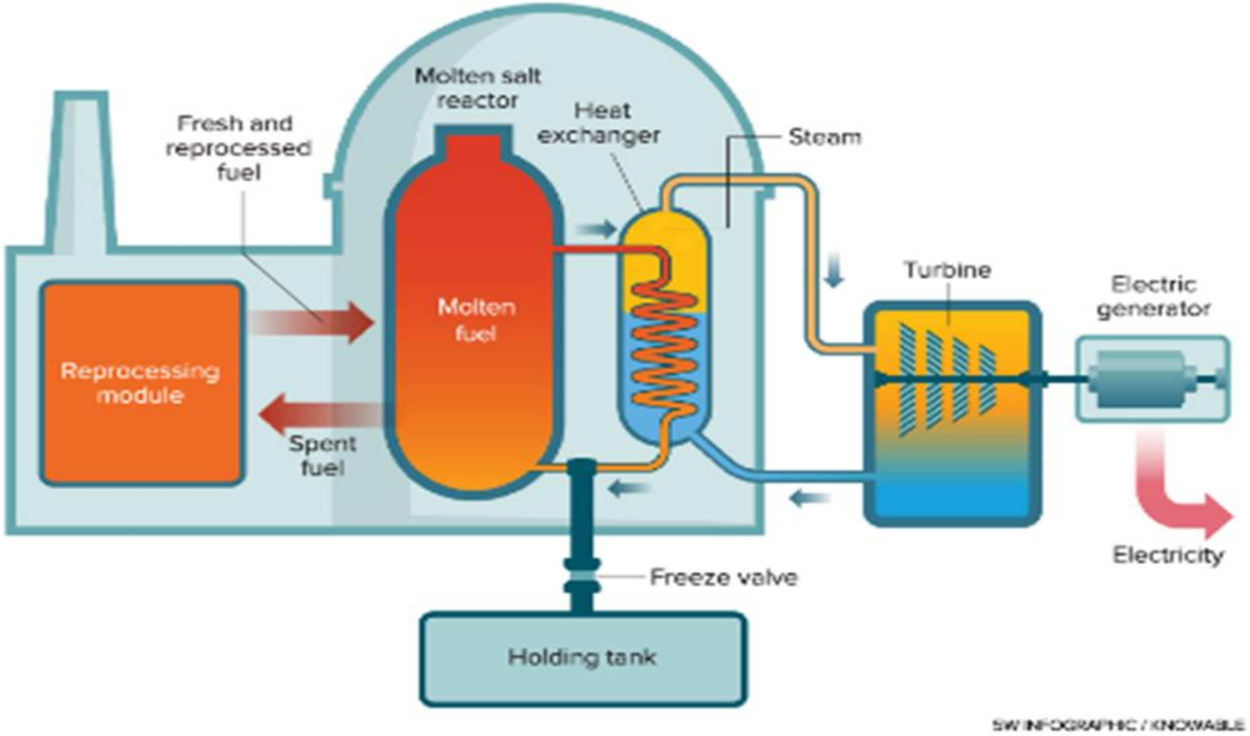
- Awarded US$80 million in US DOE Advanced Reactor Demonstration Project in Oct 2020
- Plan to deploy, with utility partner Energy Northwest, to deliver the commercial scale Xe 100 by 2027
- Demo project at Idaho National Laboratory

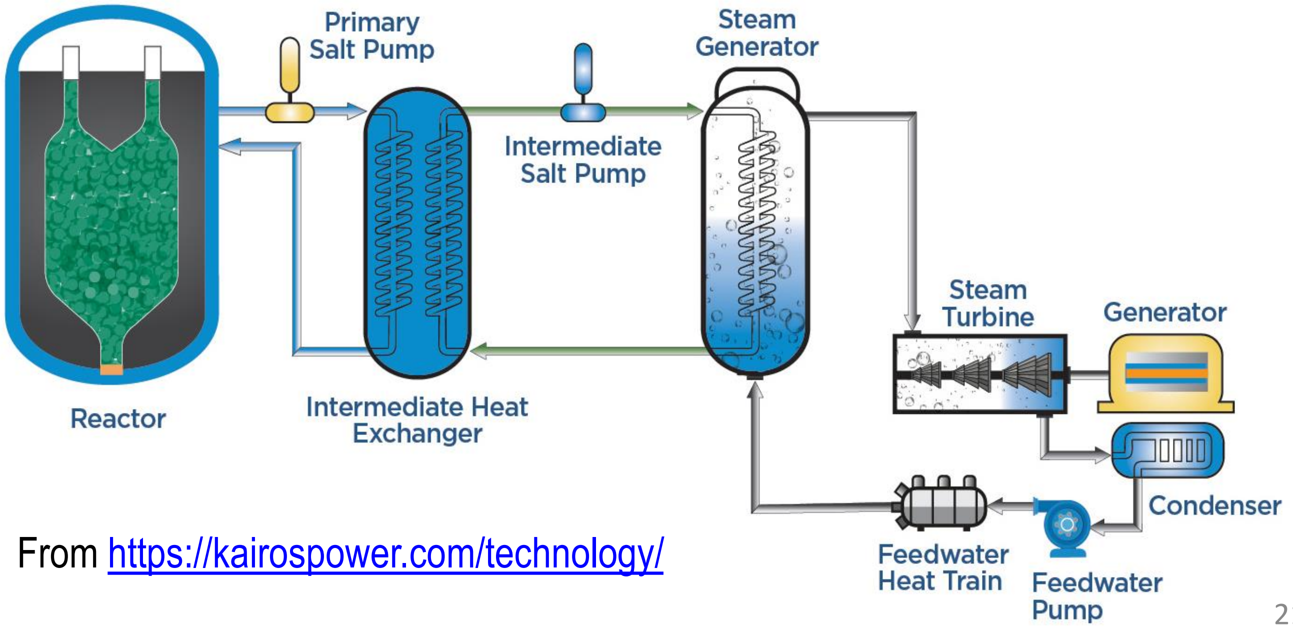
- ❑ Commercial 600 MWe NPP, known as HTR-PM600 (6 reactor modules of same design as HTR-PM connected to one steam turbine) is under development.
  - ❑ Market to replace existing coal power stations and for process heat
  - ❑ Feasibility study for 5 possible sites (3 different owners) including for 2 NPPs at Ruijin city, Jiangxi province (inland NPP site)
- ❑ Other notable designs include PBMR-400 (South Africa), GTHTR300 (Japan) and GT-MHR (Russia).
- ❑ BATAN in Indonesia plans to construct an Experimental Power Reactor (RDE, 10 MW_t) in Serpong; a detailed engineering design roadmap was launched in 2018.

https://neutronbytes.com/2016/04/09/progress-report-on-htgr-reactors-in-china-and-u-s/

Molten Salt Reactors (MSRs)

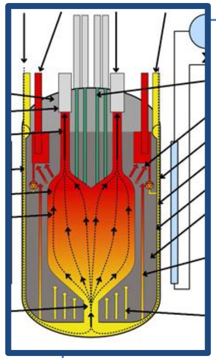
- ❑ Molten salt (e.g., $LiF\text{-}BeF_2$) as coolant
- ❑ Mainly two broad groups of MSRs:
  - ❑ Liquid fuel – fuel (UF_4) is also in molten state
  - ❑ Solid fuel (e.g., TRISO fuel) – aka fluoride cooled high temperature reactor (FHR)
- ❑ Operating at close to atmospheric pressure
- ❑ High output temperature of coolant (high boiling point of molten salt)
- ❑ Freeze plug safety mechanism for liquid fuel MSRs
- ❑ Online removal of fission products / refueling
- ❑ Still needs more R&D, especially liquid-fuel type



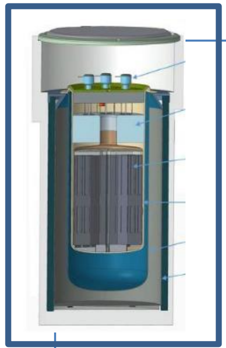


From https://kairospower.com/technology/

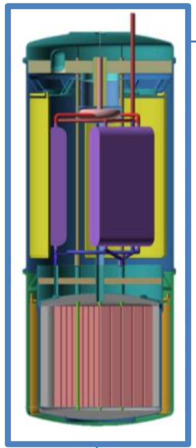
Some Notable Examples of Molten Salt Reactors



Kairos Power KP-FHR (US, 140 MWe)
- $629M cost-shared ARDP award from US DOE in 2020
- Engineering Test Unit in 2022.
- 35 MWt Hermes demo reactor scheduled for 2026.



Terrestrial Energy IMSR (Canada, 192 MWe)
- Entered the Phase 2 of Pre-license vendor design review in Oct 2018.
- Strategic Innovation Fund Award in 2020
- Planned construction in 2027 – 2031.



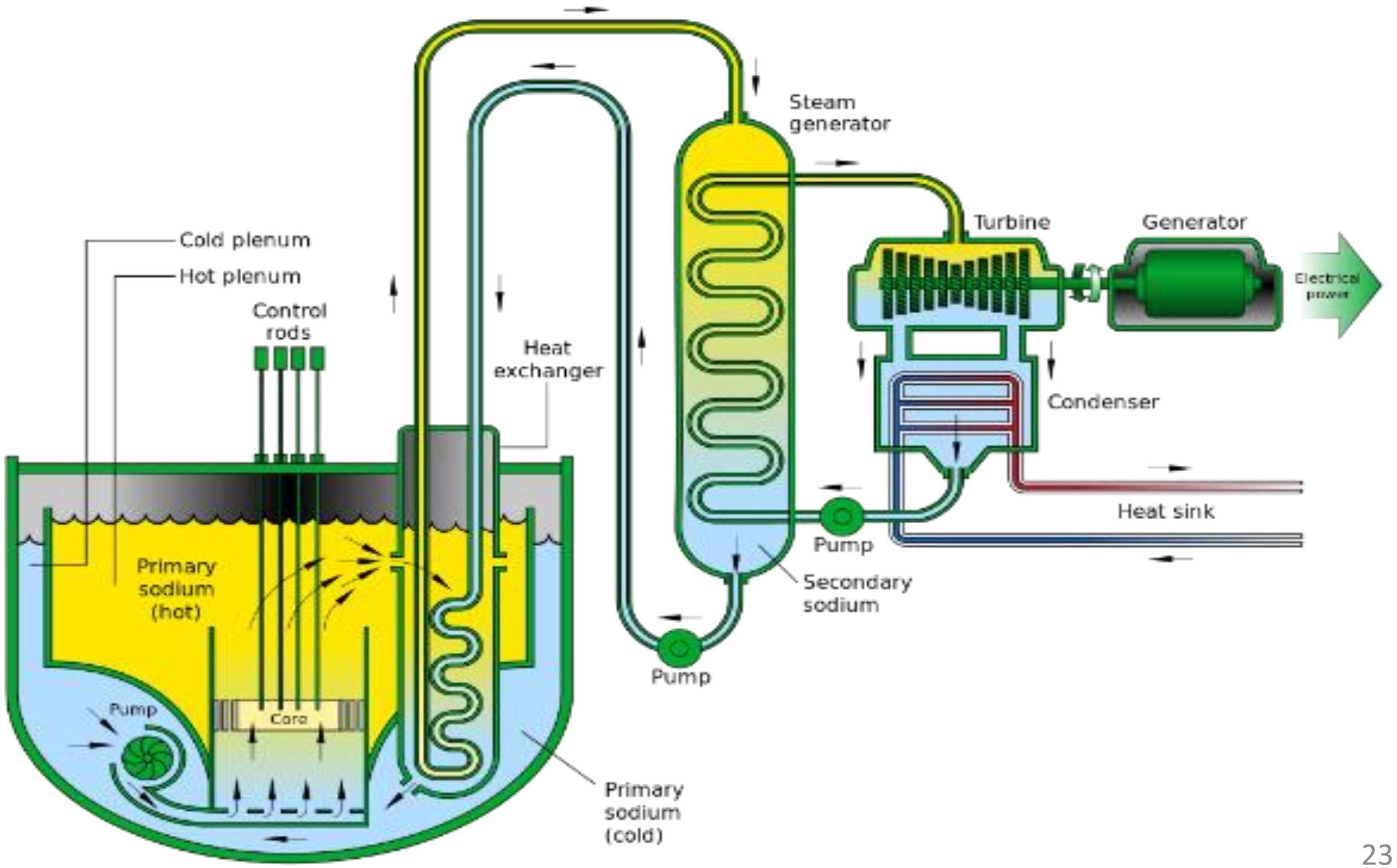
TMSR-400 (China, 168 MWe)
- Part of TMSR-LF* and TMSR-SF* program led by SINAP ($3.3 billion)
- 2 MWt TMSR-LF1 is under construction at Gansu
- A 100 MWt demonstration pebble bed plant (TMSR-SF2) by 2025
- TMSR commercial deployment is anticipated in the 2030s

Seaborg CMSR (Denmark, 250 MWt)
- NaOH moderator, deployed on barge.
- Innovation Fund Denmark grant in 2017.
- 2020 American Bureau of Shipping (ABS) Feasibility Statement for use on barge.
- Targets: Design by 2026 and first barge delivered by 2028.

* T for thorium, LF – liquid fuel and SF – solid fuel

Sodium-cooled Fast Reactors

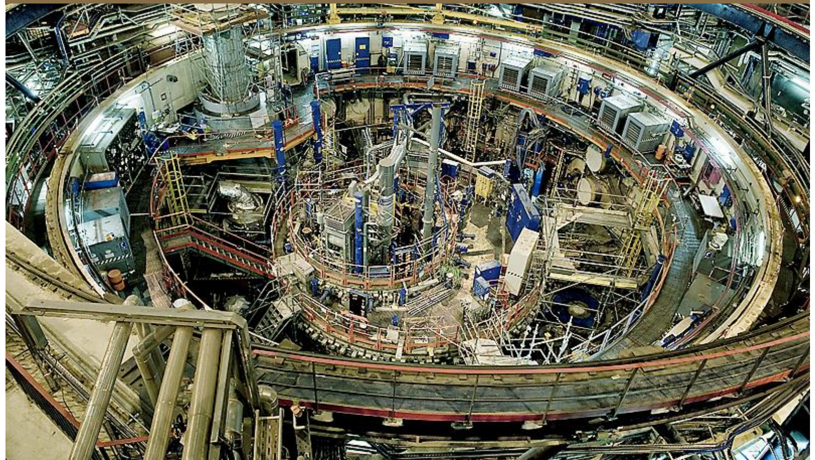
- Cooled by molten sodium (MP = 98°C, BP = 883°C).
- Operating temperature ~ 550°C $\Rightarrow$ Thermal efficiency ~ 40%
- Fast neutron reactor (no moderator).
- More efficient than thermal-spectrum neutrons to convert U-238 to Pu-239 (breeders)
- Low pressure (near atmospheric)
- Usually high-power density (300 MW/m^3) vs 100 MW/m^3 for PWR.
- Different power considered:
  - SMR (50 - 150 MWe)
  - Intermediate (300 – 500 MWe) and
  - Large (500 – 1500 MWe)
- Uses higher enriched uranium (up to 20%) cf. 3-5% for PWRs.



Sodium-cooled Fast Reactors

- More than 20 SFRs built and in operation around the world and combining nearly 400 reactor years of operation.
- Early SFRs: EBR-1 (World’s first NPP to be built at Idaho NL, 1951-62), EBR-2, Fermi 1, etc.
- Past SFRs: Phénix (France, 142 MWe, 1973-2010), Superphénix (France, 1240 MWe, 1986-98), PFR (UK,250 MWe, 1974-94), Joyo (Japan, 50 - 140 MWt, 1977-2007), Monju (Japan, 280 MWe, 1995-2017)
- Currently Operating SFRs: BN-600 (Russia, 600 MWe, since 1980), BN-800 (Russia, 885 MWe, since 2015), CEFR (China, since 2011)
- Under construction: PFBR (India, 470 MWe, 2004), Xiapu-1 (China, 682 MWe, 2017)


EBR-1 at Idaho, US


Superphénix at Creys-Malville, France


BN-800 at Beloyarsk NPP, Russia

Sodium-cooled Fast Reactors – Some Advantages

- Main advantage – more efficient use of natural uranium (99.3% U-238, 0.7% U-235).
- Operate at atmospheric pressure – safer and more cost-effective.
- Substantial thermal inertial of the sodium coolant – slower increase in temperature during accidents.
- High thermal conductivity of sodium – easier to remove decay heat.
- Lower level of actinides in spent fuels.
- Large difference between operating temperature and boiling point of sodium (~ 300°C) cf. PWRs – sodium more likely to remain in liquid state even during accident.
- Inherent safety – expansion of coolant and other structures when temperature suddenly rises causes reactivity to decrease and shut down reactor automatically.

Sodium-cooled Fast Reactors – Some Safety Issues

- Chemical reaction between sodium and air – sodium burns in air – risk of sodium fires. Inert gases (argon) to fill the space in the primary and intermediate systems.
- Violent chemical reaction between sodium and water – formation of hydrogen and heat (risk of both hydrogen and steam explosions) – if any break occurs at steam generator.
- Risk of coolant freezing when shutdown leading to structural damage due to expansion or contraction during phase change.
- Embrittlement of steels in the presence of sodium, interaction with MOX fuel, concrete.
- Optical opacity of sodium, presents specific difficulties for in-service inspection of certain equipment items.
- Partial meltdown occurred in EBR-1 and Fermi 1, sodium fires in Monju Reactor

Some Personal Predictions on Future of Fission Reactors

- **Gen III / III+ PWRs** will continue to be the main reactors to be connected to grid in the next decade and will help in reducing CO2 production.
- **Small Modular Reactors (SMRs) using PWR technologies** with passive safety features are very likely to be commercialised before 2030. The number of such reactors in uncertain at this juncture but has potential to be deployed in large numbers both in established and as well as newcomer countries.
- Inherently safe **High Temperature Gas-cooled Reactor** (HTGR) technologies can potentially be commercialised before 2030 and can play an important role to replace coal / gas boilers.
- **Molten Salt Reactors** (MSR, liquid fuel) are unlikely to be commercialized by 2030 though some FHRs may be demonstrated by then.
- **Sodium-cooled Fast Reactors (SFR)** is a matured technology that have been around and operated since 1950s but only two dozens have been built. Improvement on its safety (or its perception) is probably needed for it to be widely accepted to be deployed commercially. Idea of combination with molten salt energy storage may help but would not be unique to SFRs.
- **Hybrid systems** combining nuclear and renewables may be adopted by some countries and is the most likely pathway to achieve net zero transmission by 2050.

Hybrid System: Nuclear + Renewable Energy

OR

+

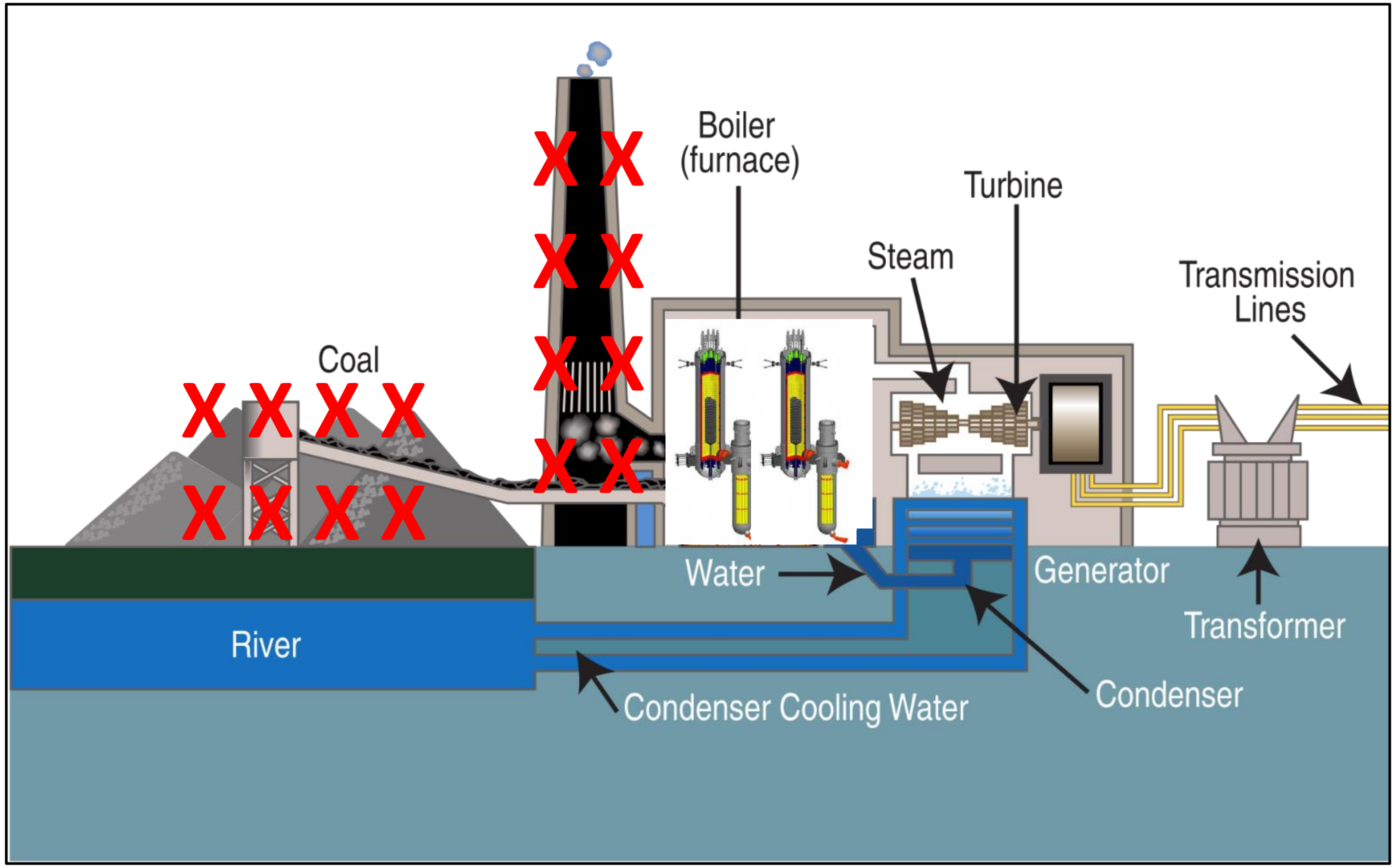
- Constant Power to Grid or as needed
- Green Hydrogen Production (especially at high temperature)
- Desalination and other industrial applications

Nuclear: Concentrated, always on, matured technology, safety can be further improved

Renewable: Naturally replenished, large land areas needed, intermittent

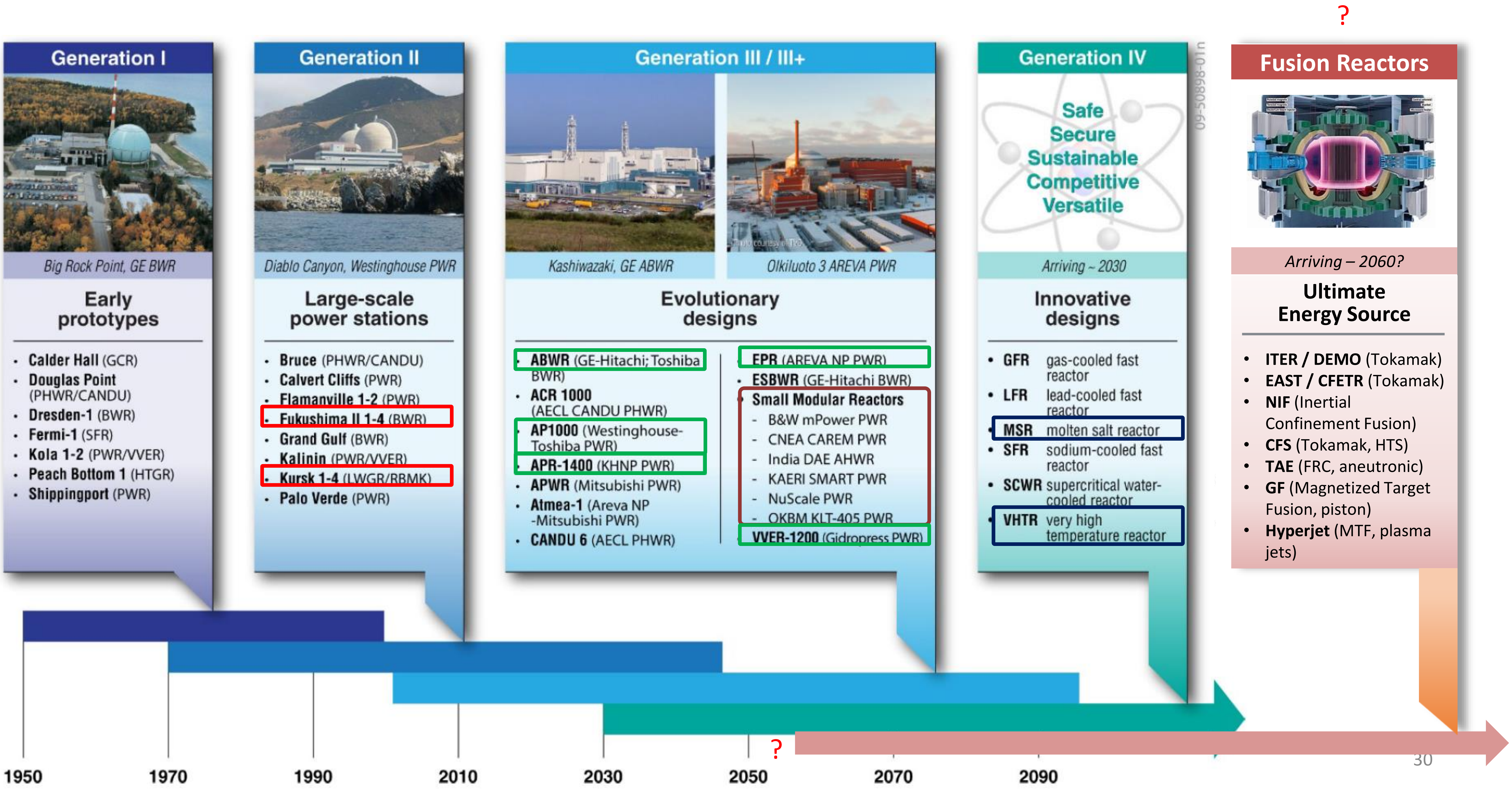
Replacing Boiler in Fossil Fuel Power Plants with Nuclear Reactors

- It would make the greatest impact if we can replace just the “boiler” in the fossil fuel power plants but keep the rest of the plants – cut cost of building new nuclear power plants!



- Needs reactors that are extremely safe (failproof) so that they can operate near population centres where current plants are and produce the same amount of thermal power needed.

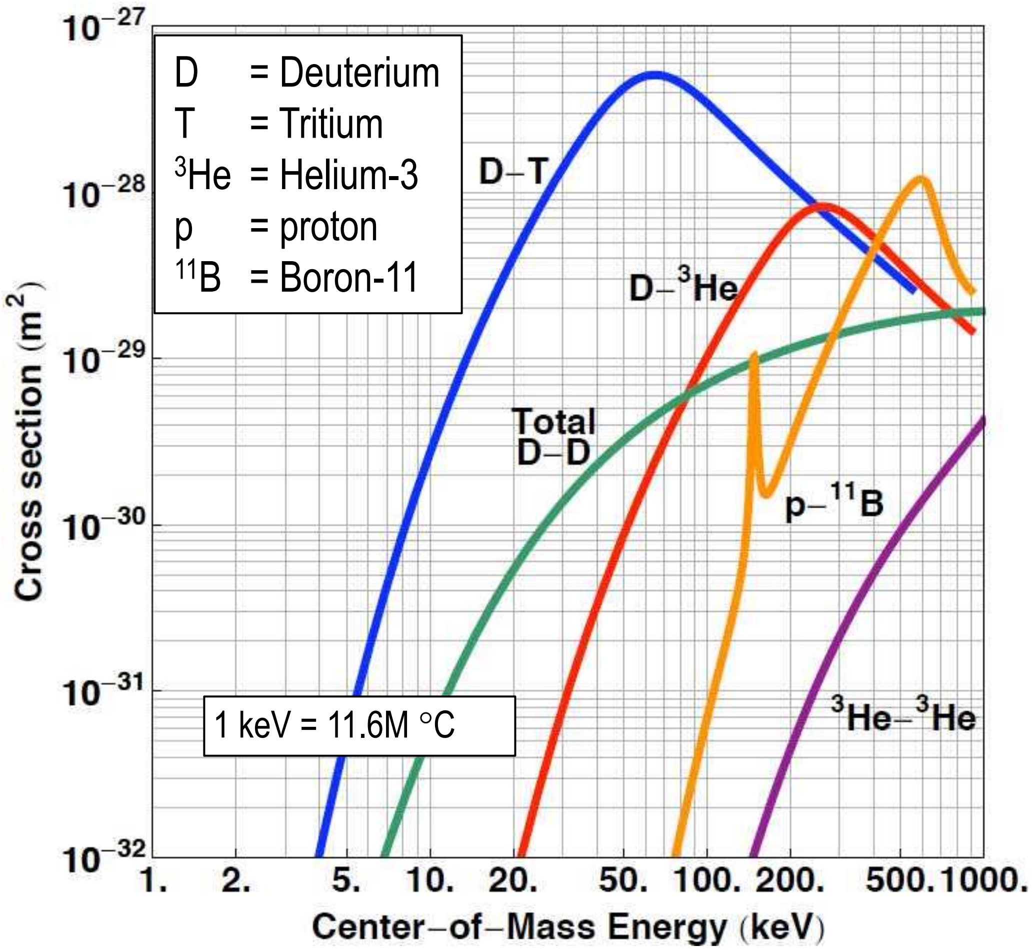
Evolution of Nuclear Reactors including Fusion Reactor



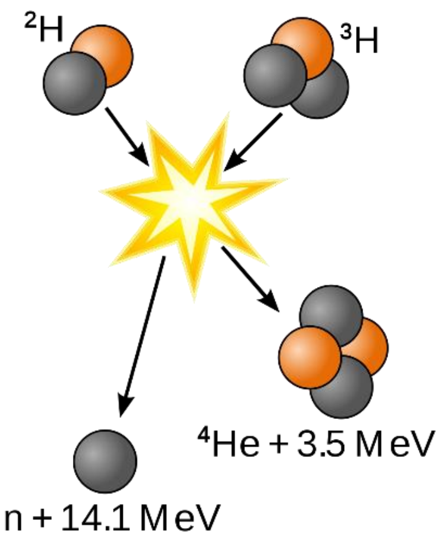
Fundamentals of Fusion Reactors

- Fusing two light nuclei (hydrogen isotopes) instead of splitting heavy nuclei (e.g. uranium, plutonium).
- Deuterium-tritium (D-T) fusion requires least stringent conditions (but still > 100 million °C)
- Energy per reaction is extremely high*.

Probability of fusion for various light nuclei vs their energy (temperature)



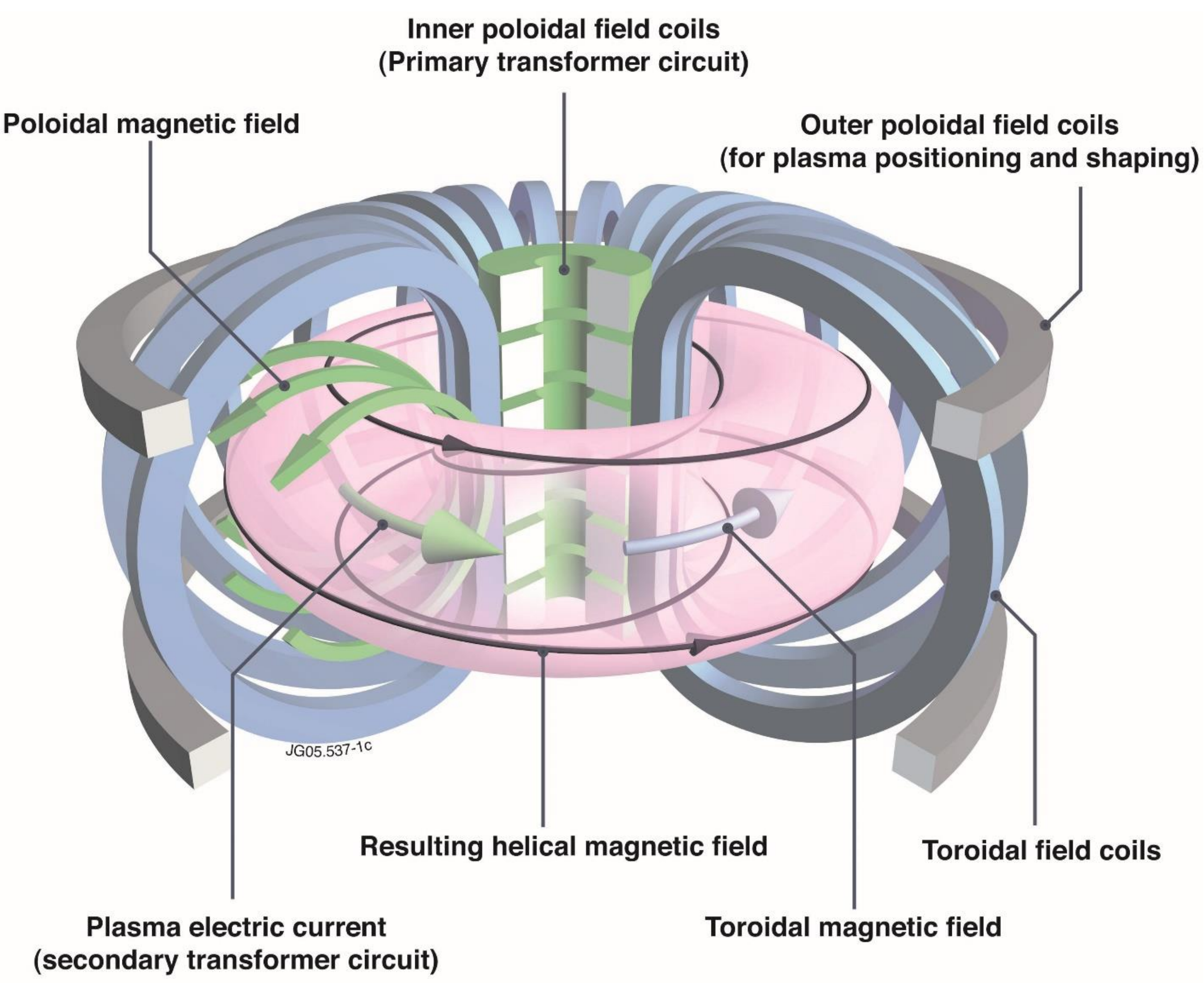
Deuterium-tritium (D-T) fusion



* 1 MeV = 1.6 x 10^{-13} J. 1.5 g of tritium (^{3}H) fused with 1 g of deuterium (^{2}H) will produce 6.7 x 10^{11} J or 187,000 kWh of energy – enough to provide 6 households with 1 kW power uninterrupted for 1 year (assuming 30% conversion to electricity)

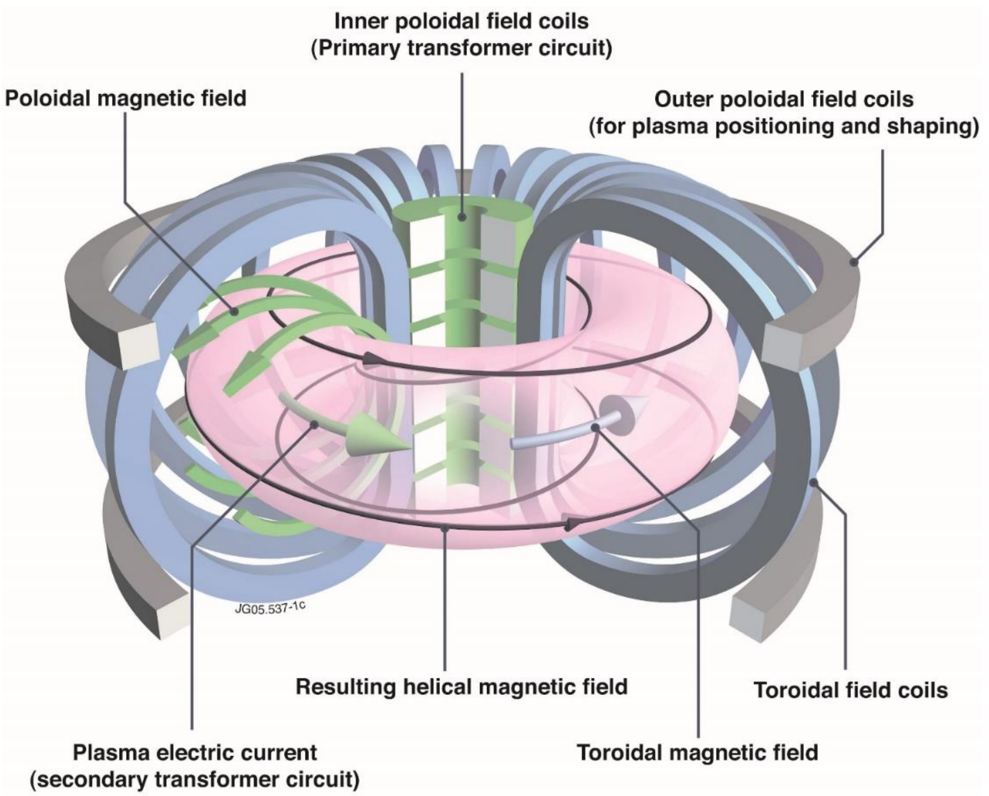
Nuclear Fusion (Tokamak)

- Hot plasma (+ve ions & electrons) needs to be confined
- Tokamak is the most proven design, e.g., ITER, CFS, JET, EAST, etc.
- High magnetic field may be produced by superconducting cables.
- High temperature, high density and long confinement time needed to achieve significant fusion.
- Important also to develop systems
  - To produce tritium (fuel)
  - To transfer heat from plasma
  - Can withstand neutron irradiation



Nuclear Fusion (Safety)

- No long-lived radioactive products (such as Pu-239) nor fission products (e.g., Cs-137, Sr-90, etc.) that can contaminate large land areas
- No risk from uranium fuel cycle – mining (tailings), enrichment process, reprocessing or storage of spent fuels
- Any accident $\Rightarrow$ immediate termination of the fusion process. There is no decay heat that can cause any meltdown
- Tritium needed as fuel has half-life of 12.3 years. Produces only weak beta particles – can easily be shielded. Need to prevent its contamination in drinking water.
- Neutrons could be absorbed by other nuclei in surrounding materials and cause these materials to be radioactive. These generally have short half-lives – no long-term storage issue.



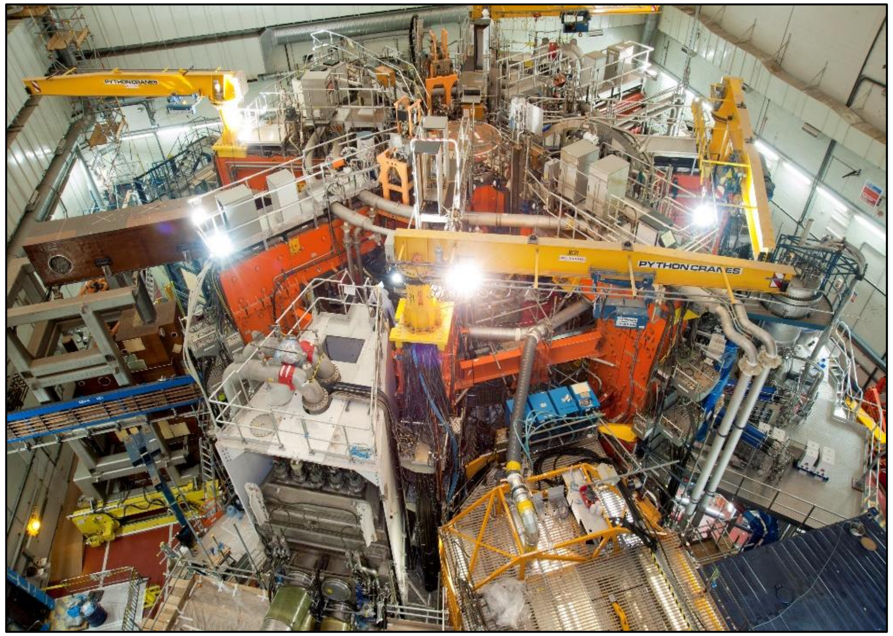
Nuclear Fusion (Challenges and Prospect)

What are some of the challenges?

- Extreme conditions needed
- Structural integrity issues at extreme magnetic field.
- Negligible amount of natural tritium.
- Transfer of heat from fusion to generate electricity.

How far is it from commercialisation?

- No fusion reactors have ever reached breakeven*.
- Unlikely to achieve commercialisation before 2050.
- High Temperature Superconductors that can operate at higher magnetic fields and temperatures can be potential game-changers.

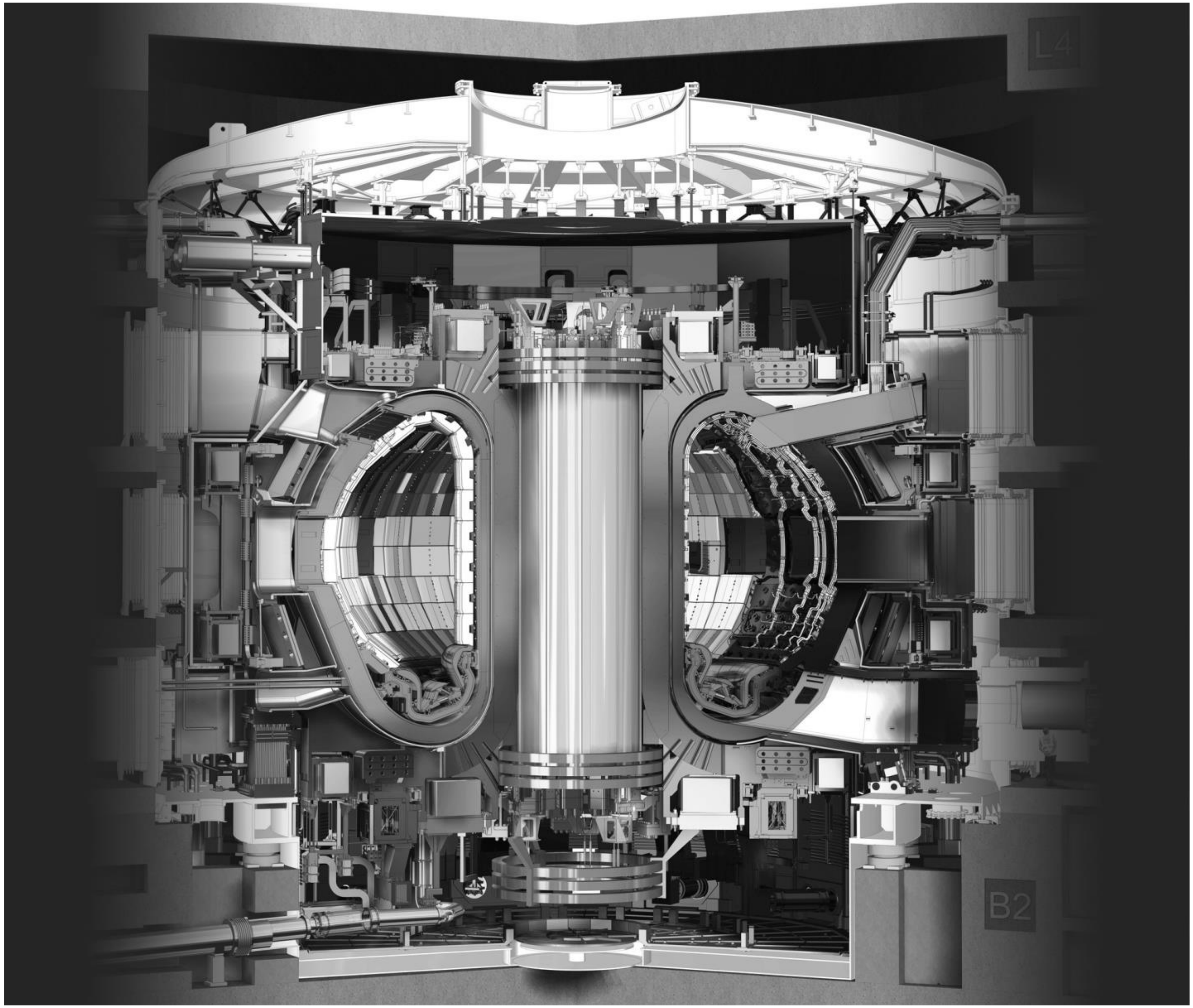


*The record for Q, fusion energy gain factor, is currently held by JET Tokamak (Joint European project), set in 1997 at **Q = ~0.67, for about 2 seconds**.

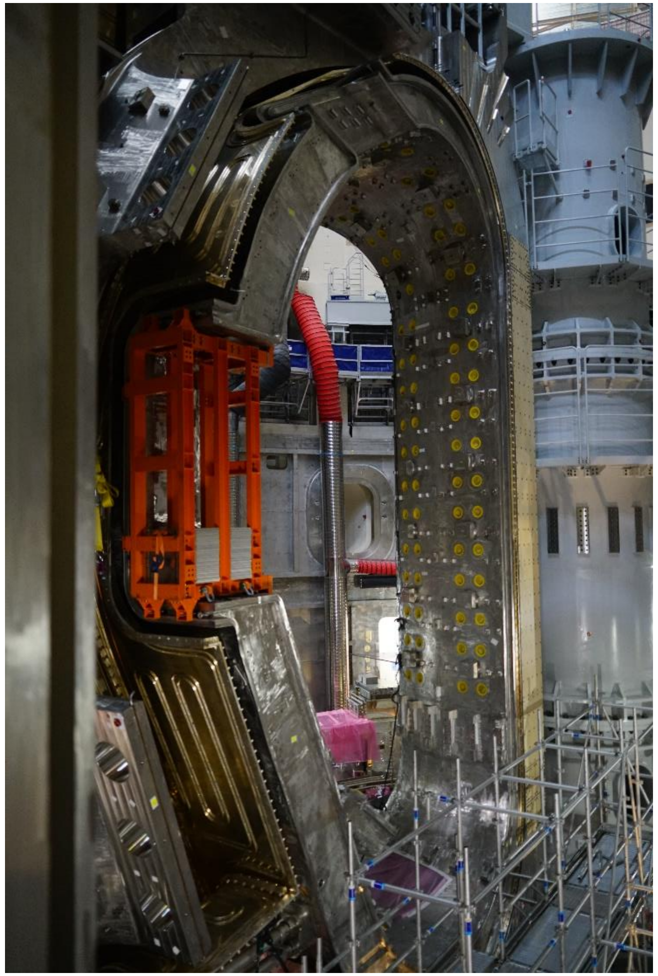
Q refers to the ratio of power generated from fusion reaction to required heating power.

ITER

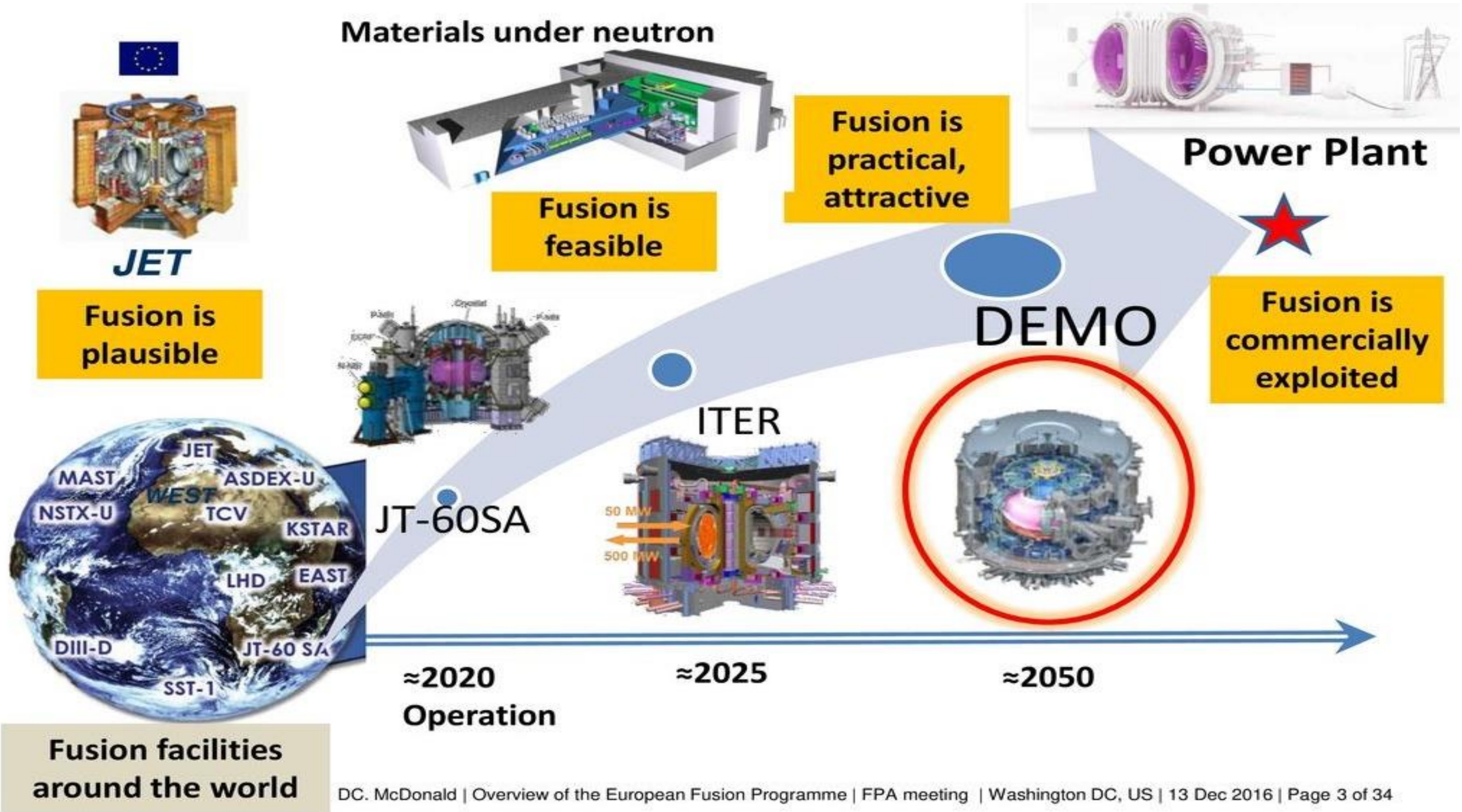
- ITER ("The Way" in Latin) largest international collaboration on Fusion in France
- Initially funded and run by European Commission, Japan, United States, and USSR; later joined by China, India and South Korea
- 500 MWt (10 x gain from input energy 50 MW)
- First plasma is expected in 2027 with D-T fusion in 2035.
- Delays are expected due to complex funding arrangements.
- Budget for construction: €5B (initial estimate) → €10B (2009 estimate) → €15B (2010 estimate) → > €20B (2016 estimate). 45% EU, 9% each for Japan, US, Russia, China, India and South Korea



Pathway to Commercial Fusion Power



One of the main magnetic field coils being put in place at ITER (Sep 2022)



Project	Input	Output	Energy Gain factor	Status
Joint European Torus (JET)	24 MW	16 MW	0.67 ✓	Achieved
ITER (current stage)	50 MW	500 MW	10 ?	Targeted
DEMOstration Power Station (DEMO)	80 MW	2000 MW	25 ?	Targeted

Chinese Fusion Programme

- Plans for Integrated research centre for fusion energy was approved in Apr 2019 under the China's 13th Five-year Plan.
- Targets to demonstrate fusion power generation with CFETR by 2030.
- The current Experimental Advanced Superconducting Tokamak (EAST) in Hebei, China, will provide experimental evidence and scientific support for the CFETR project.

- **2020**: Start to construct the Chinese Fusion Engineering Testing Reactor (CFETR).
- **2030**: Complete construction of CFETR (P_f ~200 MW, tritium self-sustained)
- **2040**: Complete upgrade of CFETR (P_f ~ 1 GW, Q_{eng} > 1).
- **2050-60**: Complete construction of Prototype Fusion Power Plant (~1 GWe, Power Plant Validation).