NUCLEAR ENERGY: PRESENT STATUS, CHALLENGES AND THE RISE OF A NEW ERA

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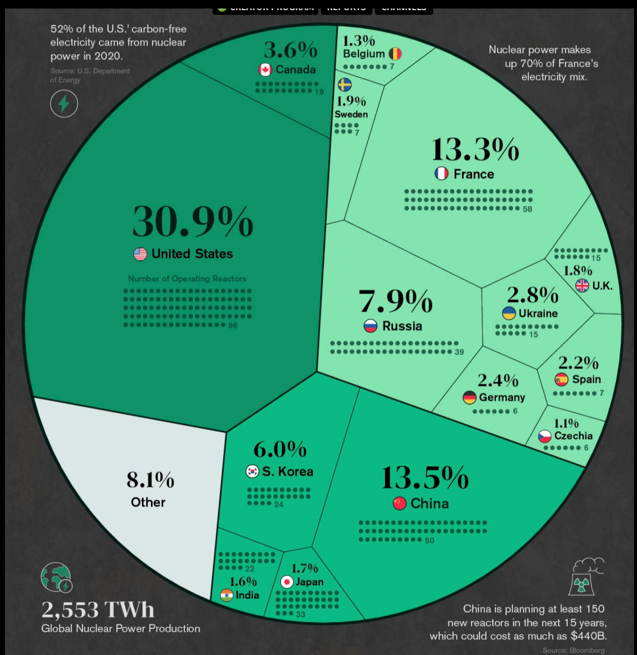
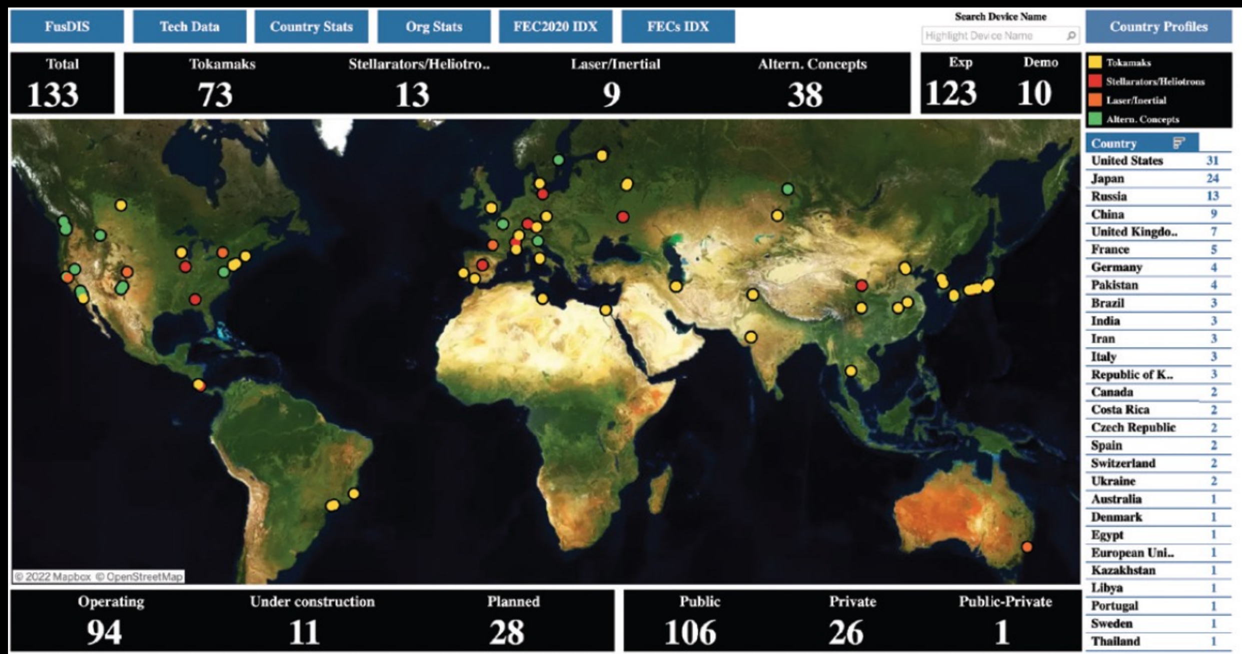
Source IAEA Director General Report 2022

Nuclear energy -Present Status

Nuclear energy – generated by large nuclear fission power plants - has been a significant source of electricity generation for decades, contributing to global energy supplies while producing low greenhouse gas emissions. As of the current state, several countries heavily rely on nuclear power, while others are re-evaluating their nuclear energy strategies due to safety concerns and the rise of alternative energy sources. Fusion has been the source of studies for decades and several countries are investing on fusion projects



Fission Nuclear Power /country



Fusion Projects

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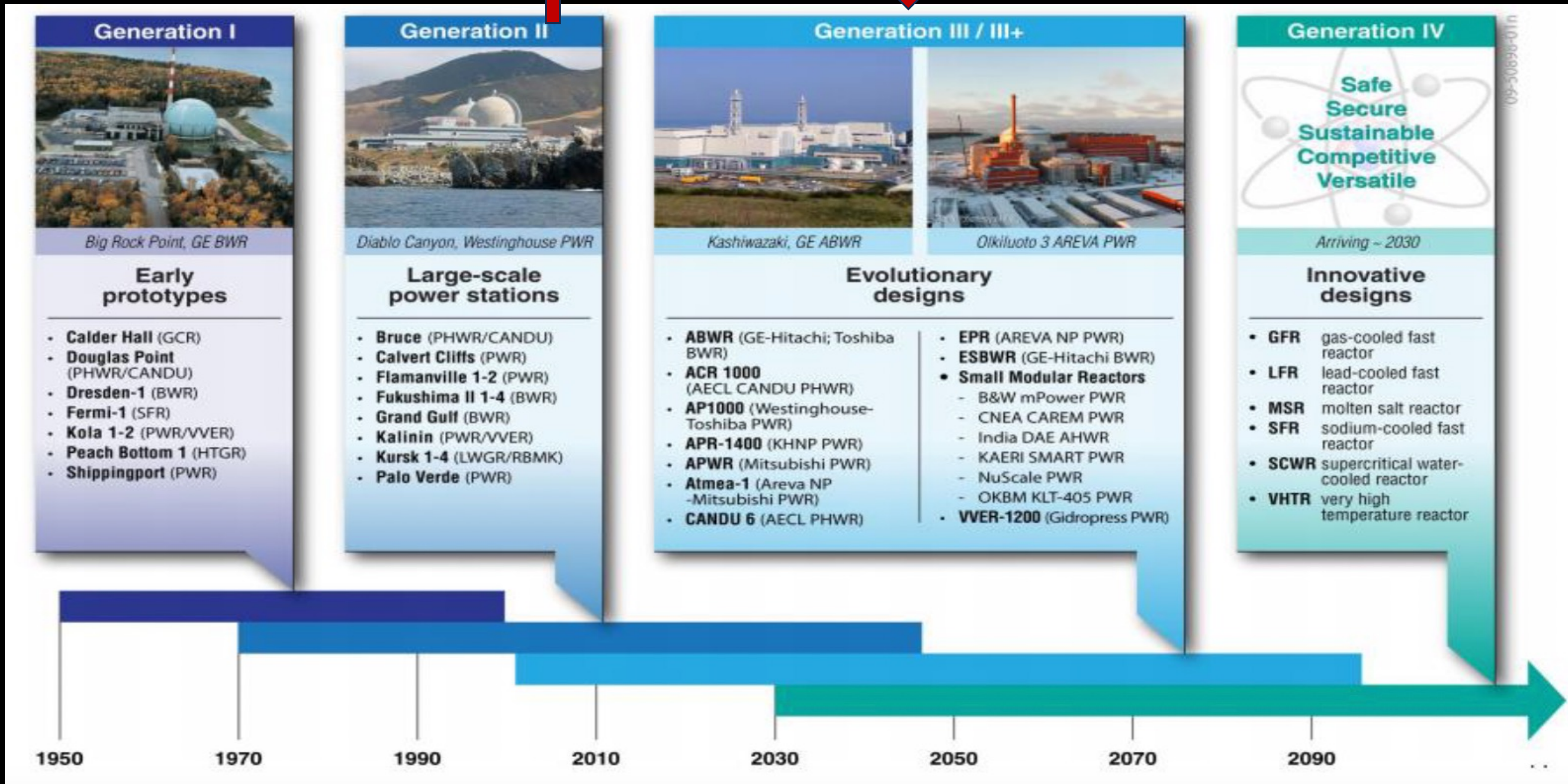
Source: Generation IV International Forum, www.gen-4.org
Slide from Varenna2023 -S. Leray

Generations of Nuclear Fission Power Plants

present

preparing



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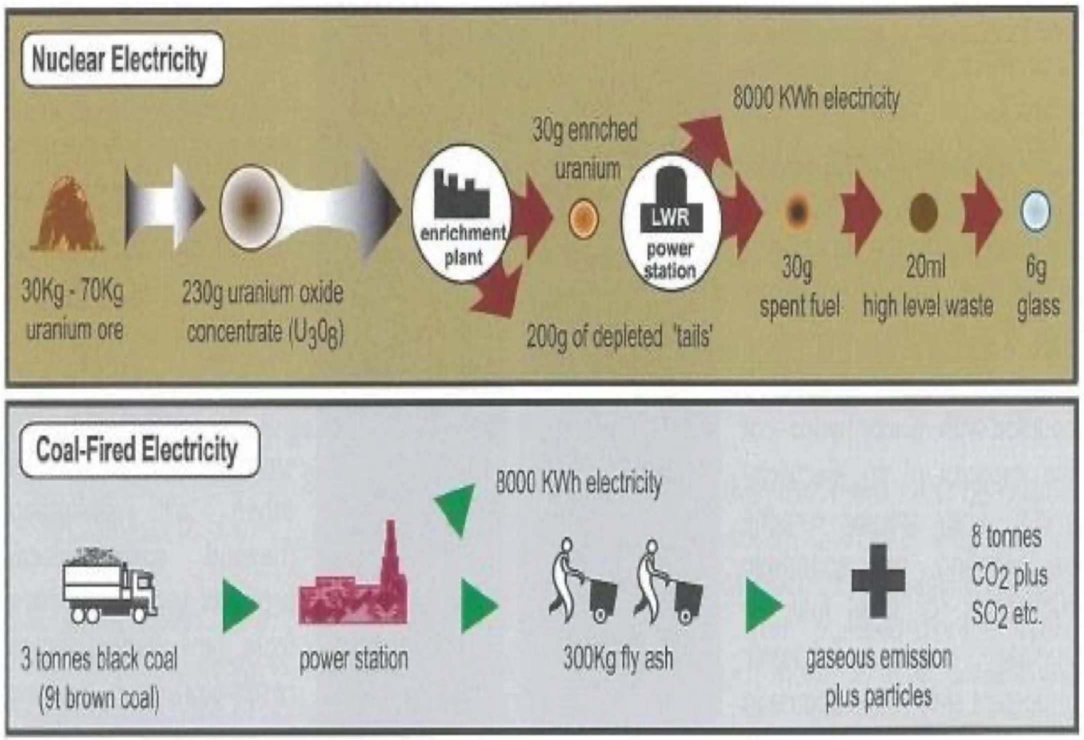
Key Features of Present Nuclear Energy I

Electricity Generation: Nuclear power plants use controlled nuclear reactions to produce heat, which is then converted into electricity. These plants provide a consistent and reliable source of baseload power, often operating at high capacity factors.

Low Carbon Emissions: Nuclear energy emits minimal greenhouse gases during electricity generation, making it an important option for reducing carbon emissions and combating climate change.

Coal produces more than 1 million times the waste (by weight of final product).



High level spent fuel product from the electricity consumption of one person's lifetime would be encapsulated in a vitrified glass disc of this size.

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Key Features of Present Nuclear Energy II

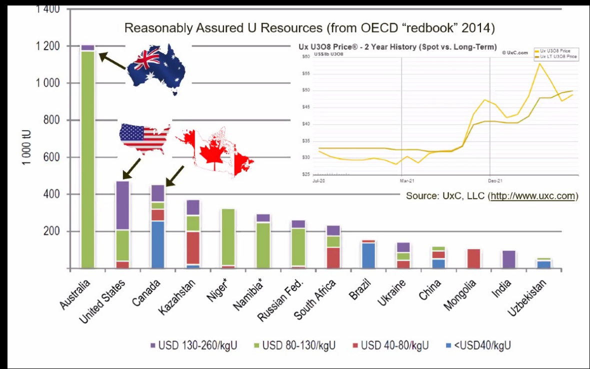
•Resource Availability:

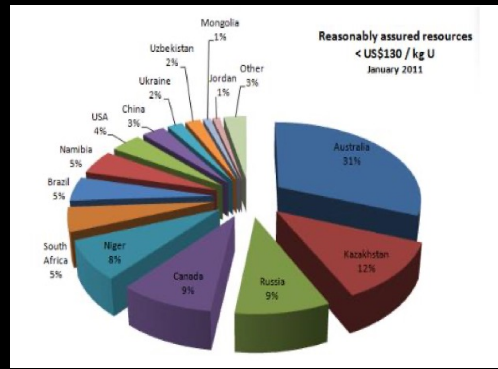
•Uranium, the primary fuel for nuclear reactors, is relatively abundant and can provide a stable source of energy for decades, if not longer.

•Quantities of mineral resources are greater than commonly perceived, and are relative to both market prices and cost of extraction.

•The world's known uranium resources increased by at least one-quarter in the last decade due to increased mineral exploration.

•Uranium should last at least until the end of the century





Very high-grade ore (Canada) – 20% U	200,000 ppm U
High-grade ore – 2% U	20,000 ppm U
Low-grade ore – 0.1% U	1000 ppm U
Very low-grade ore* (Namibia) – 0.01% U	100 ppm U
Granite	3-5 ppm U
Sedimentary rock	2-3 ppm U
Earth's continental crust (av)	2.8 ppm U
Seawater	0.003 ppm U

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Challenges I

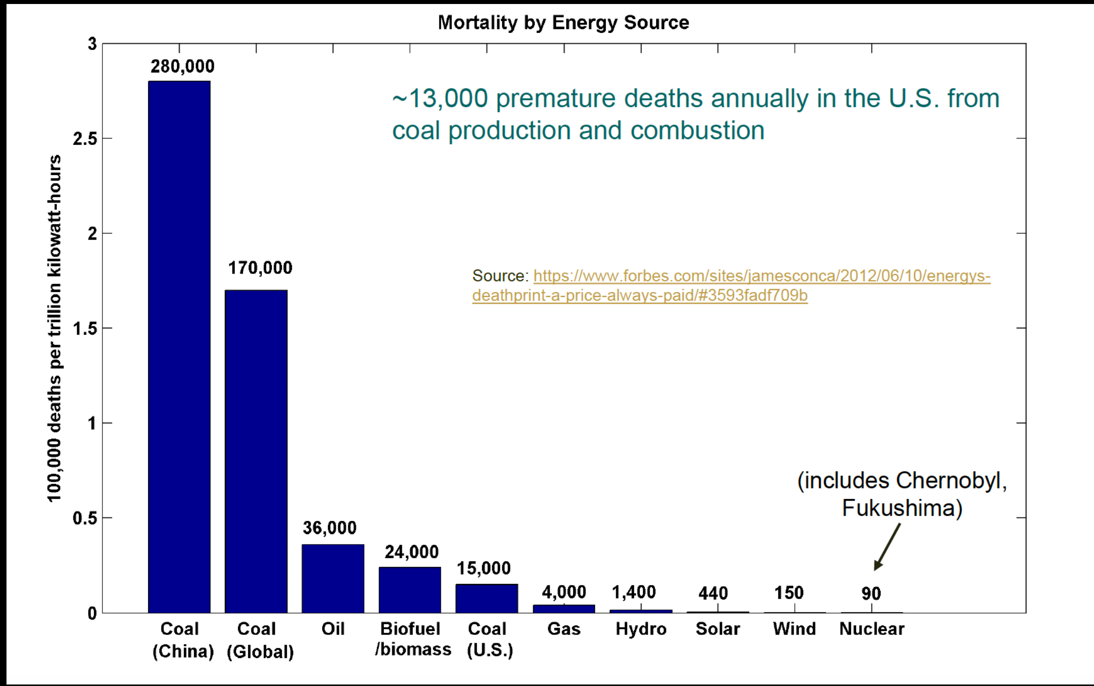
Safety Concerns: Nuclear accidents like Chernobyl and Fukushima have raised serious safety concerns and prompted re-evaluations of nuclear plant design, disaster preparedness, and reactor decommissioning.

Nuclear Accidents Worldwide

	TMI	Chernobyl	Fukushima
Location and year	US, 1979	USSR, 1986	Japan, 2011
Reactor type	PWR	RBMK	BWR (3 units)
Physical cause	Valve stuck open caused extended coolant leakage	Core instability at low power	Station blackout caused by earthquake and tsunami
Human error	Failed to recognize stuck valve, turned off pumps	Intentionally disabled safety systems to run 'experiment'	None major
Damage	Partial core meltdown	Complete core and superstructure destruction + cladding material fire	Analysis suggests 3 core meltdowns
Mitigation	Containment worked as designed	This reactor design does not have a robust containment	Containments partially failed
Release	Minimal	Massive and unmitigated, fueled by fire	Substantial, mostly into atmosphere and ocean
Public health impact	None from radiation exposure, but lots of anxiety	Radiation-induced casualties among first responders, increased incidence of thyroid cancer in locals	Minimal from radiation exposure, but much distress and several casualties from forced evacuation
Current status	Fuel removed	Debris contained within 'sarcophagus'	Safe shutdown

Each accident has been a learning experience ⇒ NPPs worldwide have gotten safer and safer

Mortality by Energy Source



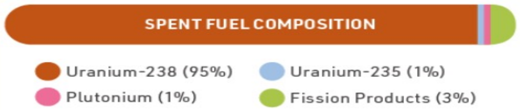
https://www.compoundchem.com/2020/04/22/nuclear-waste/

Challenges II

Nuclear Waste: Radioactive waste disposal remains a complex challenge, requiring secure long-term storage solutions to prevent environmental contamination.

Spent Fuel Composition

About 3% of spent nuclear fuel consists of radioactive fission products. In some countries, the spent fuel is reprocessed to separate the waste from uranium and plutonium.



Radioactive waste contains unstable isotopes of elements which decay and emit alpha, beta or gamma radiation. Eventually they decay into non-radioactive elements.

Half Life

HALF LIVES: UP TO 32 YEARS

Cs-137 Sr-90 Cm-243 Cm-244 Co-60

HALF LIVES: 460-24,000 YEARS

Th-229 Pu-239 Pu-240 Am-241 Am-243

HALF LIVES: 77,000-16,000,000 YEARS

Nb-94 I-129 Cs-135 Tc-99 Th-230 Np-237

As well as the radioactivity produced by nuclear waste, it also produces heat as isotopes decay. This poses issues for storage and disposal.

Types of Waste

LOW LEVEL WASTE (LLW)

90% of all radioactive waste (by volume)
1% of the total radioactivity of all waste

LLW is defined as not exceeding 4 giga-becquerels per tonne (GBq/t) of alpha activity or 12 GBq/t of beta-gamma activity.

INTERMEDIATE LEVEL WASTE (ILW)

7% of all radioactive waste (by volume)
4% of the total radioactivity of all waste

ILW produces more radiation than LLW, but doesn't generate as much heat as HLW. It includes metal fuel cladding.

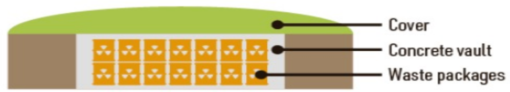
HIGH LEVEL WASTE (HLW)

3% of all radioactive waste (by volume)
95% of the total radioactivity of all waste

HLW is defined as producing more than 2 kilowatts per metre cubed of heat due to its radioactivity. It requires shielding during transport and cooling before permanent disposal. It includes used fuel and separated waste.

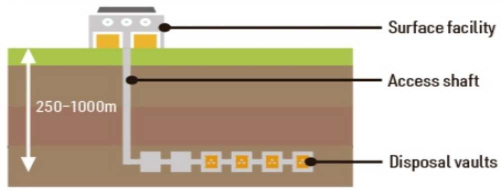
Waste Disposal

NEAR-SURFACE DISPOSAL



Low level waste's radioactivity is usually compacted into steel canisters and stored in concrete vaults underground. When full, vaults are sealed, covered and left. They ensure no significant radiation reaches the surface.

DEEP GEOLOGICAL DISPOSAL



Intermediate and high level waste generate heat and greater levels of radioactivity. Most countries plan to use deep geological disposal. The rock and soil acts as a barrier to the radiation. Before this, high level waste is incorporated into glass and stored for up to fifty years to allow heat to dissipate.

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Nuclear Energy: The Rise of a New Era

This new era is characterized by the following key developments:

1. **Advanced Reactor Designs:** Next-generation nuclear reactors are being developed with enhanced safety features, improved efficiency, and reduced waste production. Small modular reactors (SMRs) and advanced fast reactors are among the innovative designs gaining attention.

2. **Use of nuclear energy beyond electricity**: heat generation, H production, water desalinisation, energy storage…

3. **Nuclear Fusion:** nuclear fusion holds the promise of virtually limitless and clean energy. Projects like ITER (International Thermonuclear Experimental Reactor) aim to achieve controlled fusion reactions. Industry is booming with small fusion reactors. New concepts are being proposed

4. **Innovation in Waste Management:** Research is ongoing to develop more effective and secure methods for managing and disposing of nuclear waste, including advanced reprocessing techniques.

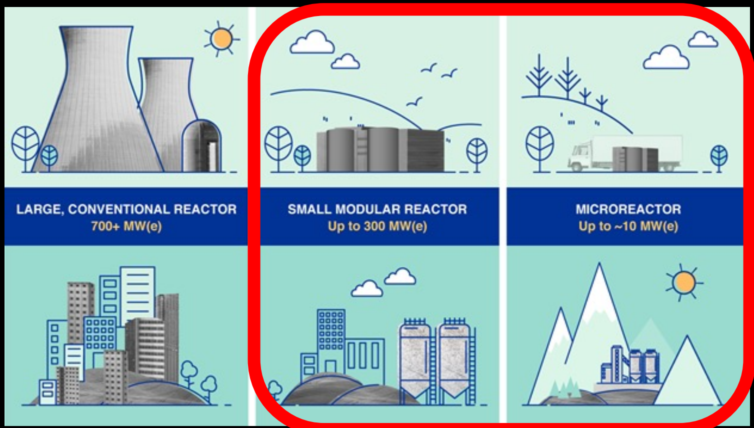
5. **Public Engagement:** Public understanding and acceptance of nuclear energy are being addressed through education, transparency, and open dialogue.

Reinventing nuclear power with SMR

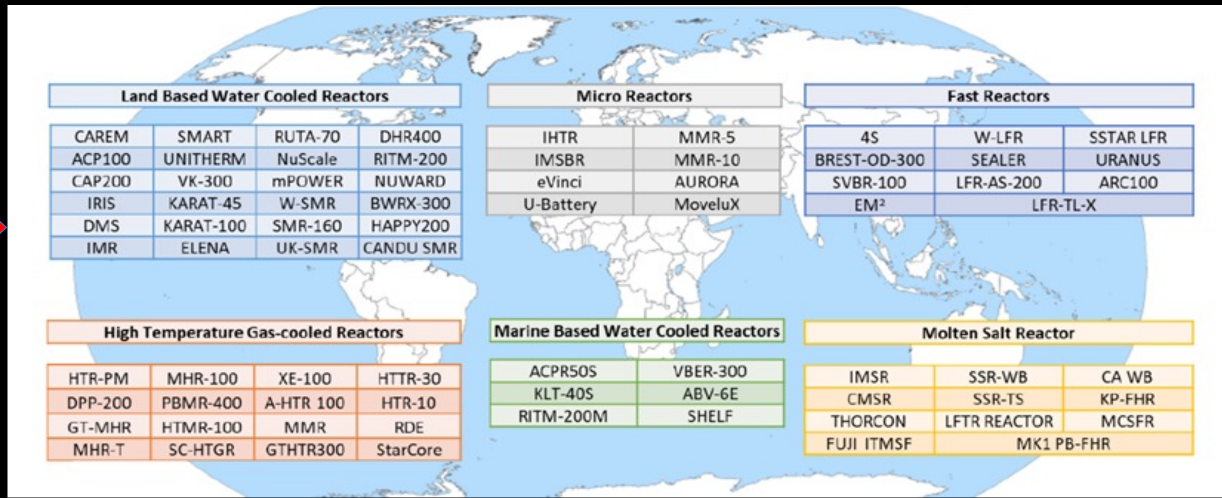
S. Sarrade ANIMMA 2023

Source : Generation 4 Forum

- from GW to MW



SMR, AMR and MMR
more than 70 concepts under study worldwide



Land Based Water Cooled Reactors

CAREM	SMART	RUTA-70	DHR400
ACP100	UNITHERM	NuScale	RITM-200
CAP200	VK-300	mPOWER	NUWARD
IRIS	KARAT-45	W-SMR	BWRX-300
DMS	KARAT-100	SMR-160	HAPPY200
IMR	ELENA	UK-SMR	CANDU SMR

Micro Reactors

IHTR	MMR-5
IMSBR	MMR-10
eVinci	AURORA
U-Battery	MoveluX

Fast Reactors

4S	W-LFR	SSTAR LFR
BREST-OD-300	SEALER	URANUS
SVBR-100	LFR-AS-200	ARC100
EM²	LFR-TL-X	

High Temperature Gas-cooled Reactors

HTR-PM	MHR-100	XE-100	HTTR-30
DPP-200	PBMR-400	A-HTR 100	HTR-10
GT-MHR	HTMR-100	MMR	RDE
MHR-T	SC-HTGR	GTHTR300	StarCore

Marine Based Water Cooled Reactors

ACPR50S	VBER-300
KLT-40S	ABV-6E
RITM-200M	SHELF

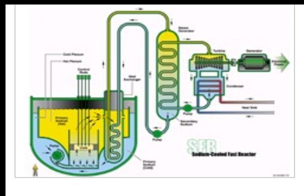
Molten Salt Reactor

IMSR	SSR-WB	CA WB
CMSR	SSR-TS	KP-FHR
THORCON	LFTR REACTOR	MCSFR
FUJI ITMSF	MK1 PB-FHR	

Source : IAEA

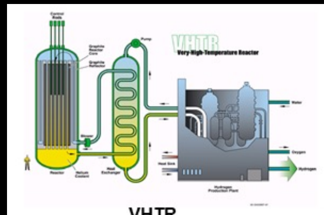
A large number of concepts

- Light water reactors of the 3rd generation (PWR & BWR) P=pressurized, B=boiling
- 4th generation reactors (AMR) A=Advanced
- Intrinsically VERY SAFE!!!



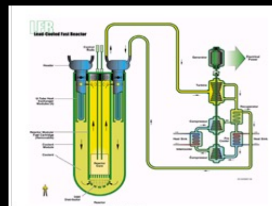
SFR
Sodium-cooled fast reactor

Sodium Cooled Fast Reactor



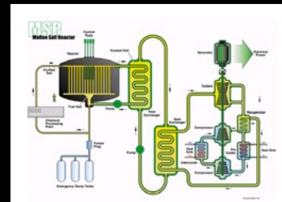
VHTR
Very high temperature reactor

Very High Temp Reactor



LFR
Lead-cooled fast reactor

Lead Cooled Reactor



MSR
Molten salt reactor

Molten Salt Reactor

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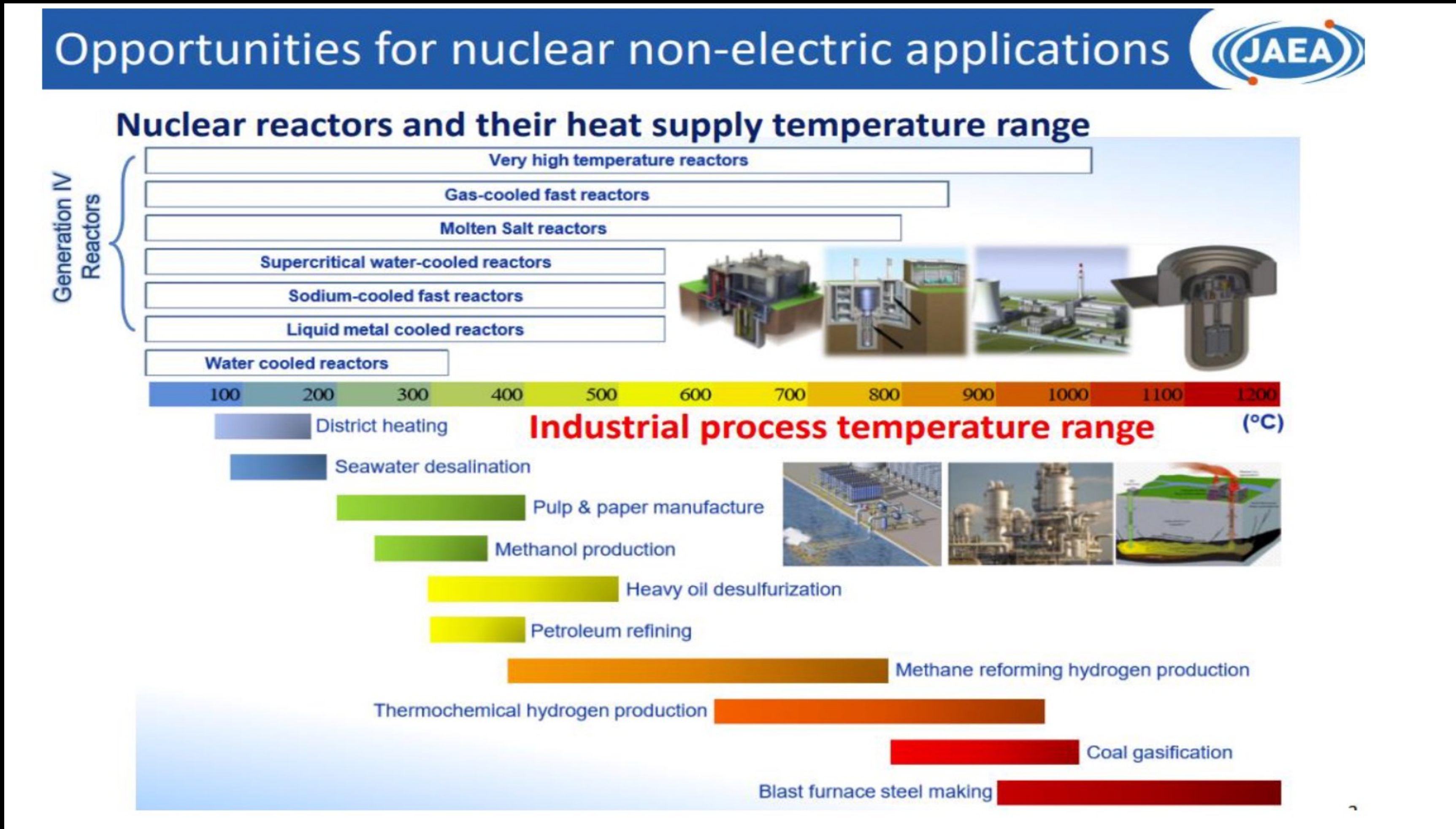
FromXinL. Yang, JAEA,
https://nucleus.iaea.org/sites/INPRO/df16/Day-1/Keynote_YAN.pdf

Use of nuclear energy beyond electricity



Reinventing nuclear power with SMR

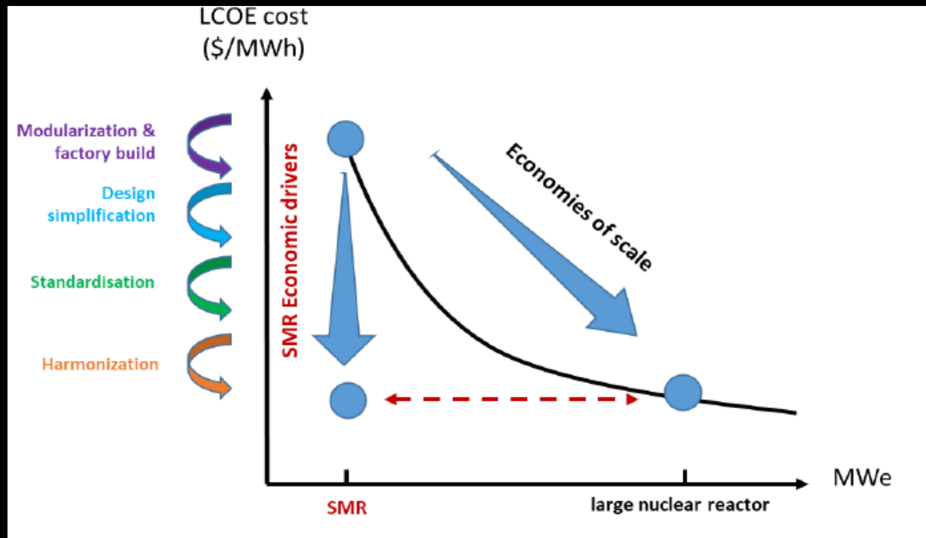
Source : Third way, NICE Initiative

New use cases for nuclear power

- Network integration and balancing
- Energy hub and remote sites
- Replacement of coal plants
- Heating and industrial heating networks
- Hydrogen & e-fuel
- Desalinization

•New approach to nuclear reactor design

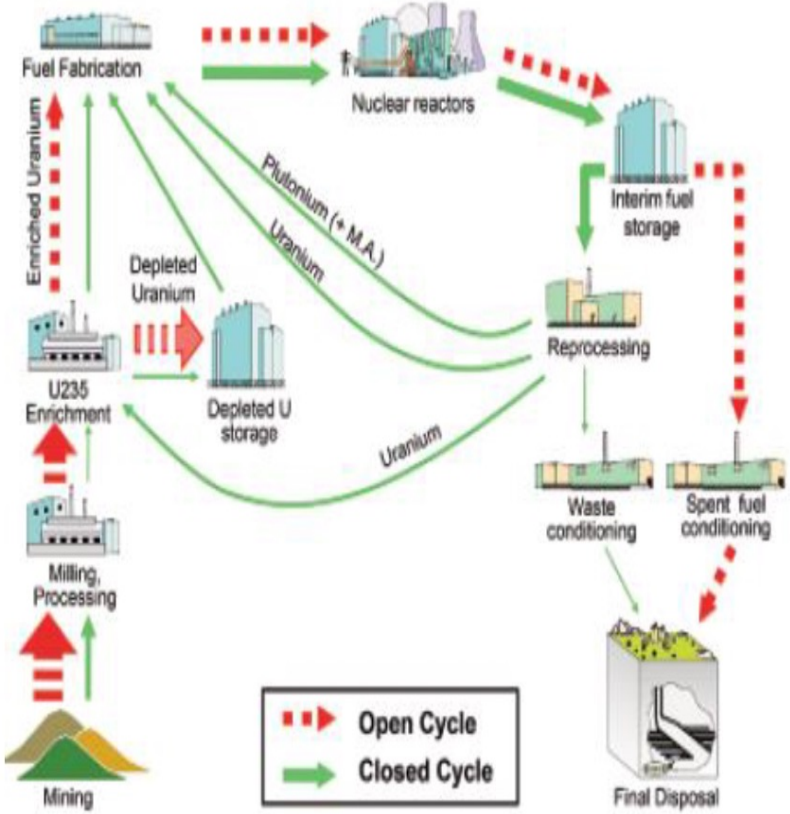
- Simplicity
- Passive safety and absence/reduction of off-site countermeasures
- Prefabrication – modularity
- Production in series



From: Varenna2023 -S. Leray

Waste: Cycle Options

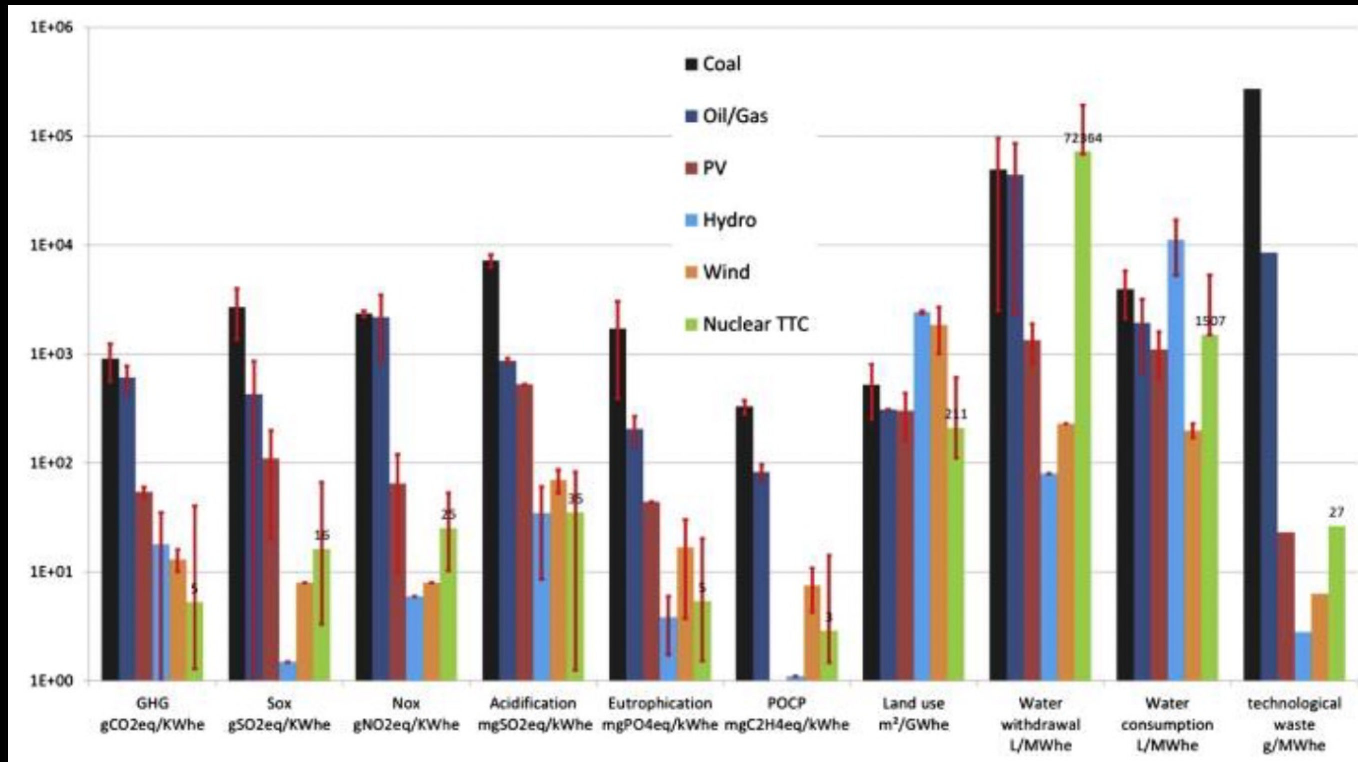
- **Two options:**
  - Open cycle: direct disposal of spent fuel (US, Sweden, Finland...)
  - Partially closed cycle: reprocessing to extract Pu and make MOX fuels (France, Japan, Russia, China...)



Nuclear Waste Disposal: Environmental Impact

Ch. Poinssotet al. / Energy 69 (2014)

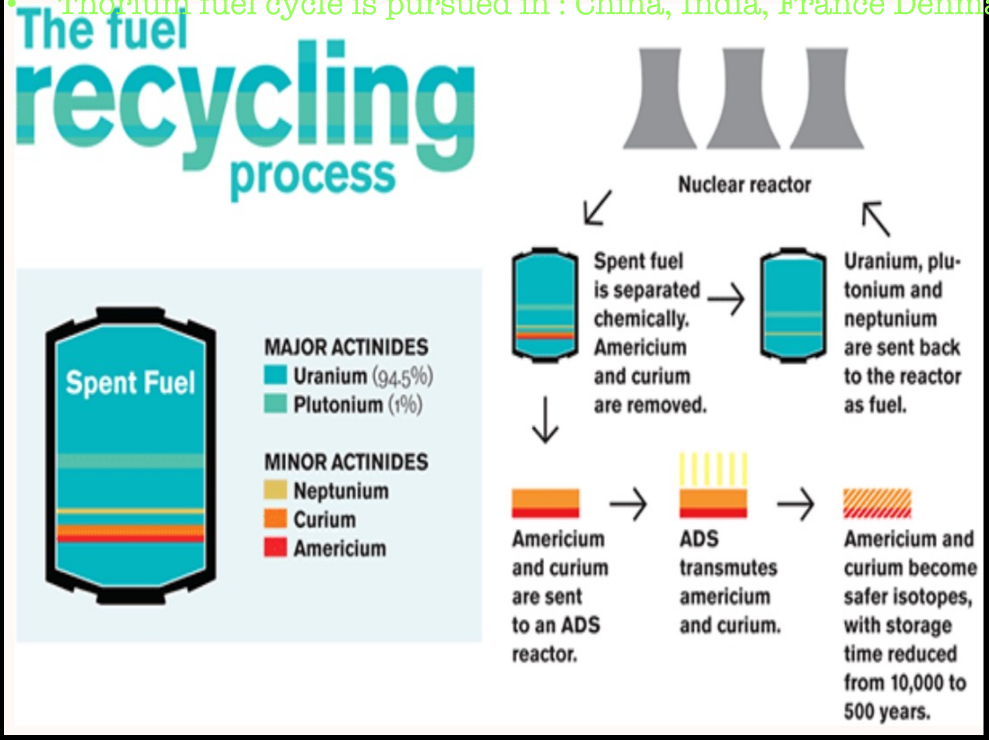
- Green-House-Eases emissions (GHG, gCO2eq/kWhe)
- Atmospheric Pollution (mg/kWhe)
  - SOx
  - Nox
- Water Pollution (mg/kWhe),
  - Acidification
  - Eutrophisation
  - POCP (photochemical ozone creation potential)
- Land-Use (m2/GWhe)
- Water Consumption (l/MWhe)
- Water Withdrawal (l/MWhe)
- Production of Technological Waste (g/MWhe)

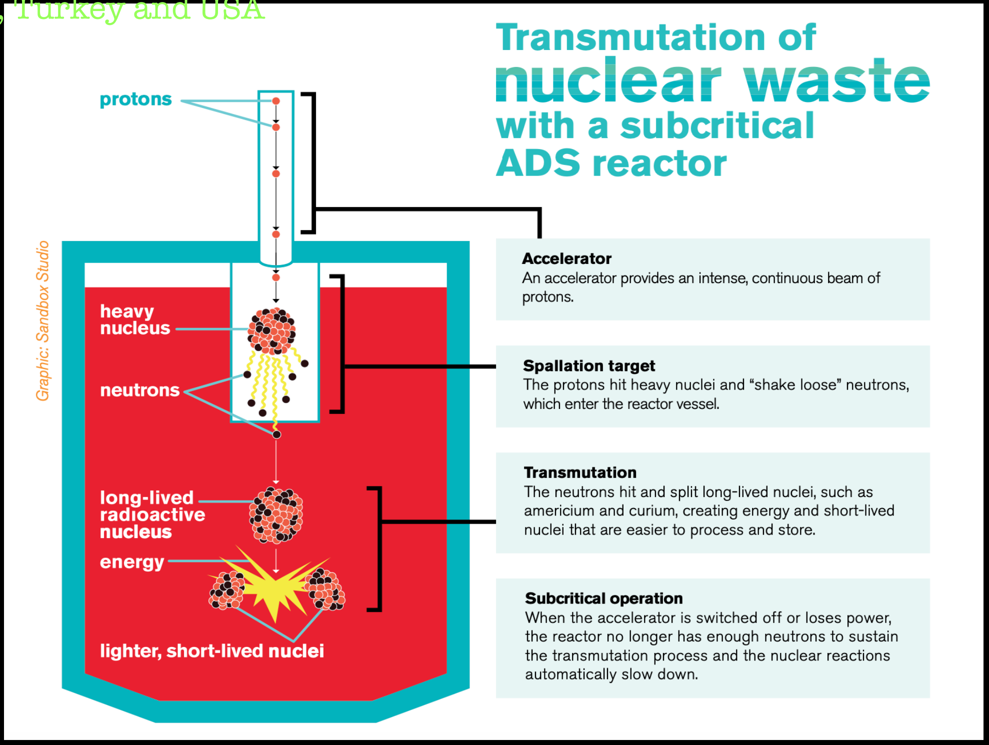


symmetry | volume 9 | issue 1 | february 2012

Transmutation of Nuclear Waste

- Use of Accelerator Driven Systems (ADS) to generate a beam of particles to help transform spent nuclear fuel into a re-useable form
- It could reduce the time required for long-term geological storage from 300,000 years to 500 years.
- Uses the abundant thorium, as a safer, cleaner, more proliferation-resistant fuel for energy production in nuclear reactors.
- EUROTRANS Project→ MYRRHA, the Multipurpose hYbrid Research Reactor for High-end Applications , Belgium
- Prototype projects GUINEVERE and Venus, (TRANSNMUTEX (CERN startup)
- Project X at Fermilab could be used as a demonstrator
- Thorium fuel cycle is pursued in : China, India, France Denmark, Turkey and USA





Thorium Cycle and Energy Amplifier

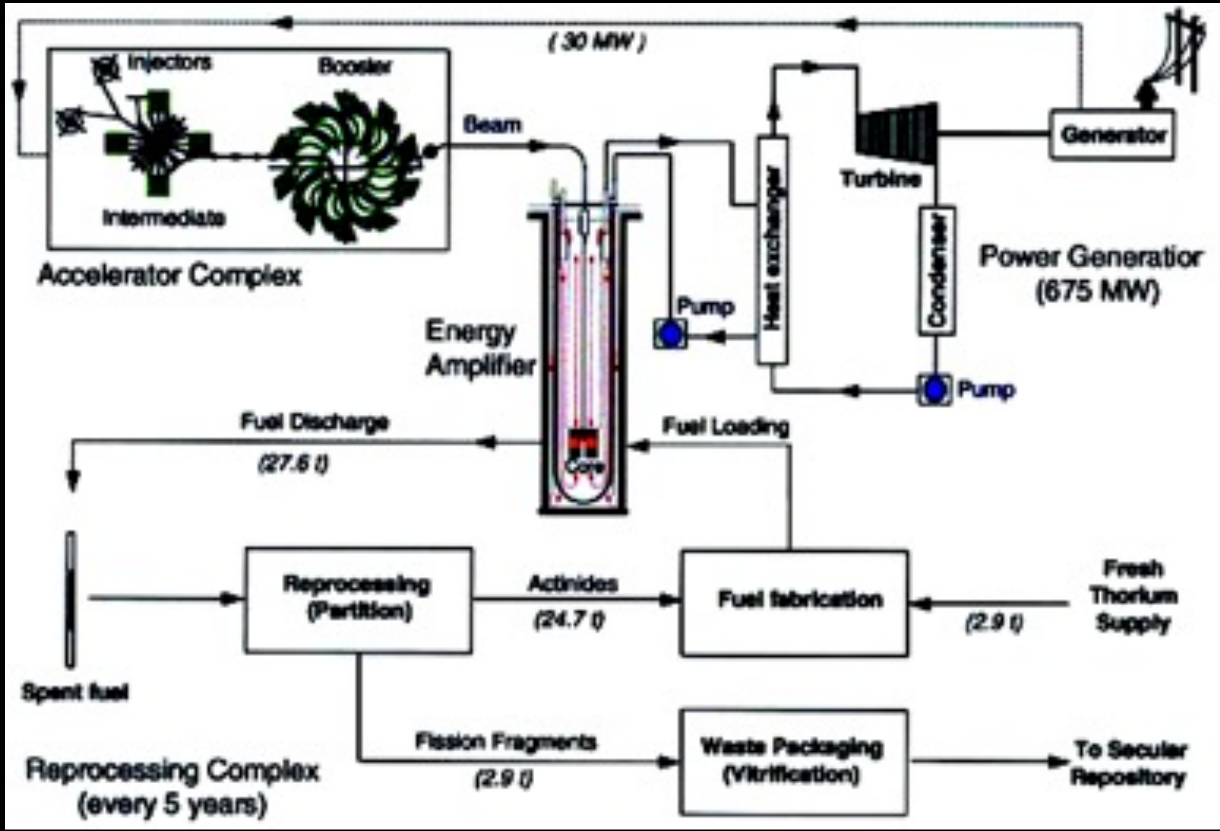
Thorium: 232Th is not itself fissile but is 'fertile'
neutron absorption leads to ^{233}U, which is fissile ^{232}Th (n,γ) → ^{233}Th (22min) → ^{233}Pa (23d) → ^{233}U(1.6x105y)

Accelerator-driven transmutation of waste (ATW) and Energy Amplifier

*The **system generates electricity from thorium** whilst continuing to burn radioactive waste*

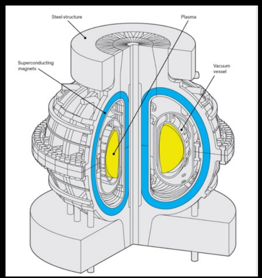
Proposed by Nobel Prize Winner and CERN former director general Carlo Rubbia in 1993

Thorium is an abundant resource (much more than uranium) and supplies could last thousands of centuries



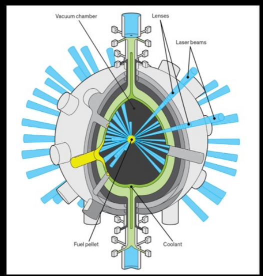
Current Fusion Technologies

Magnetic Confinement Fusion



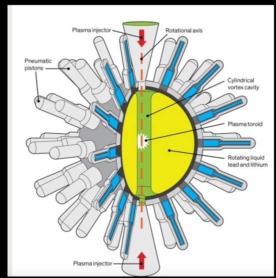
Tokamak JET, ITER
Powerful toroidal magnets and hot plasma

Inertial Confinement Fusion



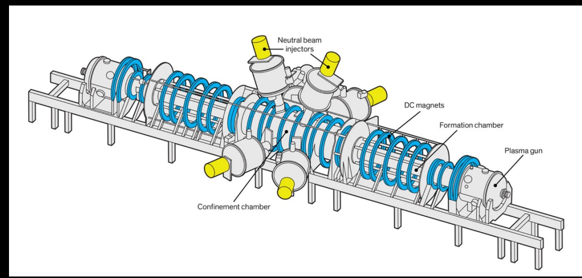
Powerful pulsed laser or ion beams on pellets

Magnetized Target Fusion



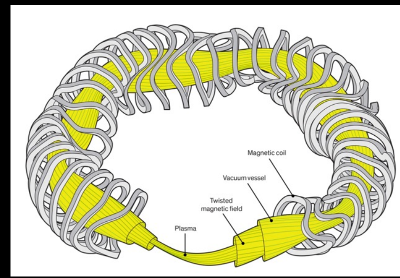
Hybrid approach
Combining magnetic and inertial confinement

Field Reversed Configuration



Uses plasma guns to accelerate two plasmas into each other and then heats them with particle beams.

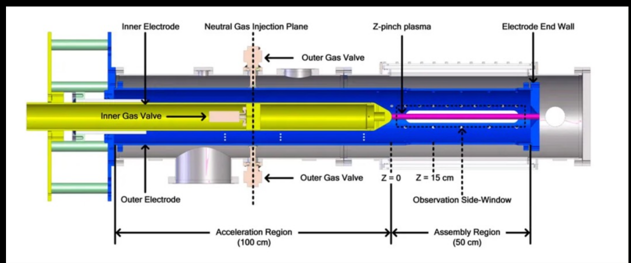
Stellarator



Spiralling ribbon shape produces high-density plasma that's symmetrical and more stable than a tokamak's, allowing the reactor to run for long periods of time.

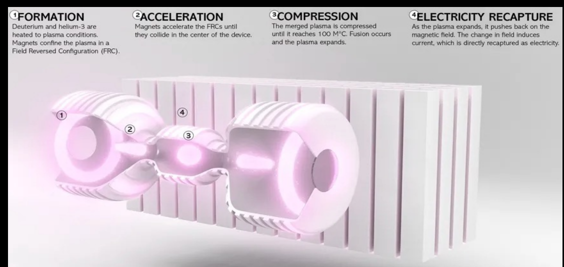
Novel "Compact" Ideas

ZAP FUzeQ Reactor = Z-pinched D plasma



~2m

Helion: D+He plasma collision



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MIT SPARC-CFS Demonstrator =2-T coil

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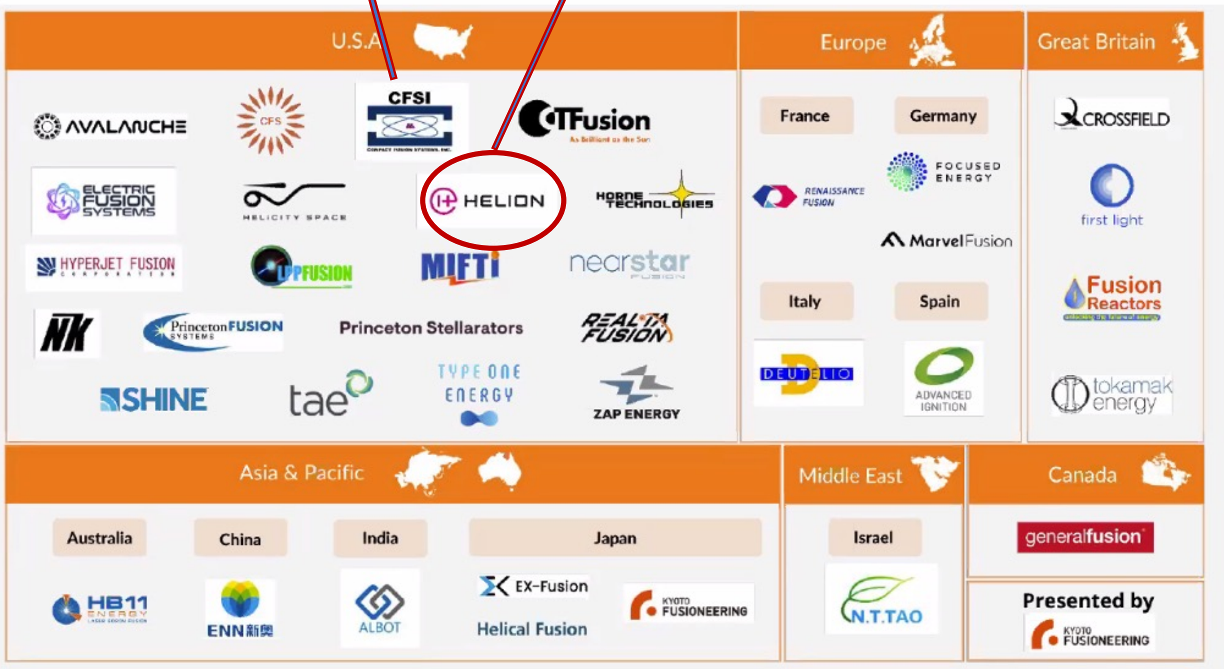
Nuclear Fusion and Private Industry

Private Fusion Industry has experience staggering growth

Commonwealth **Fusion** Systems
SPARC-MIT

Spinoff from Boeing



- 5.5 B$ raised
- Over 30 companies
- Industry association
- Wider geographic spread
- Wide array of technical approaches
- Is this competition for CFS..yes.
  Is that good. Yes!

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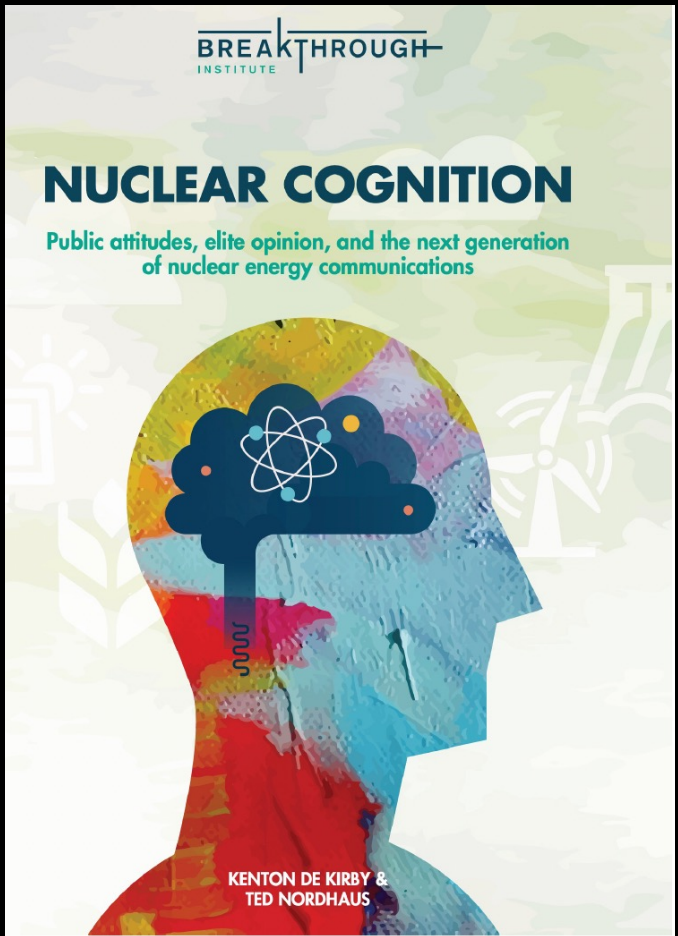
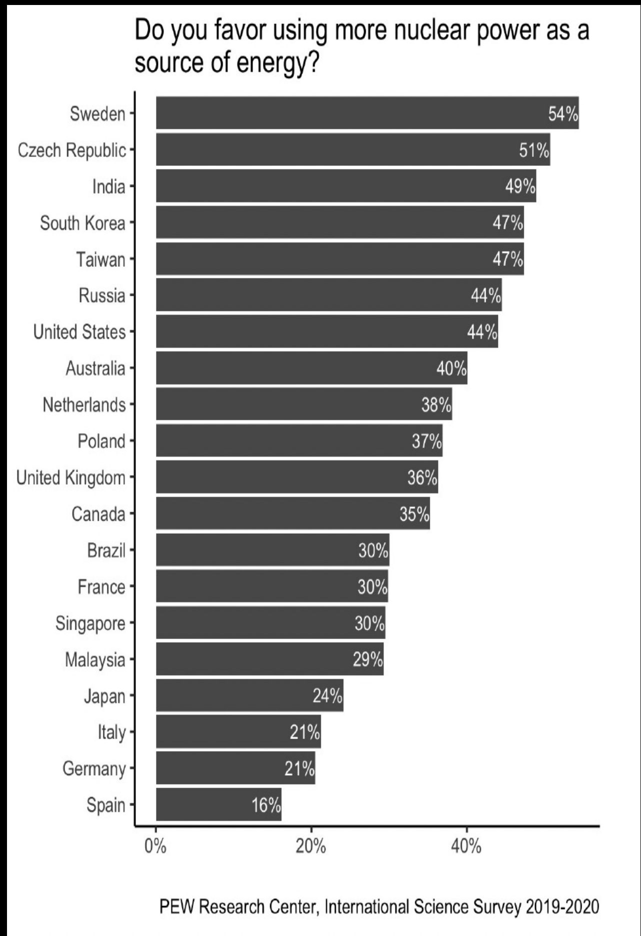
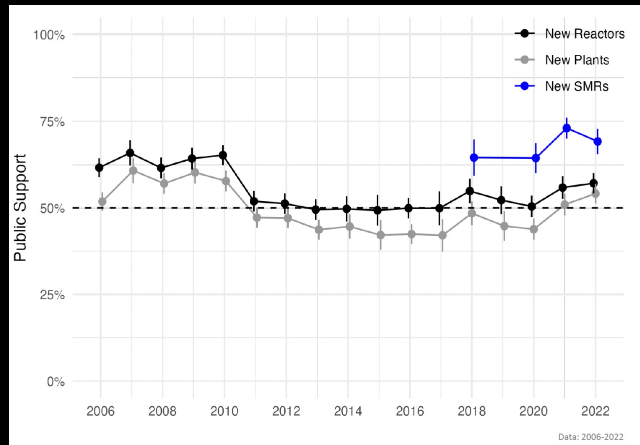
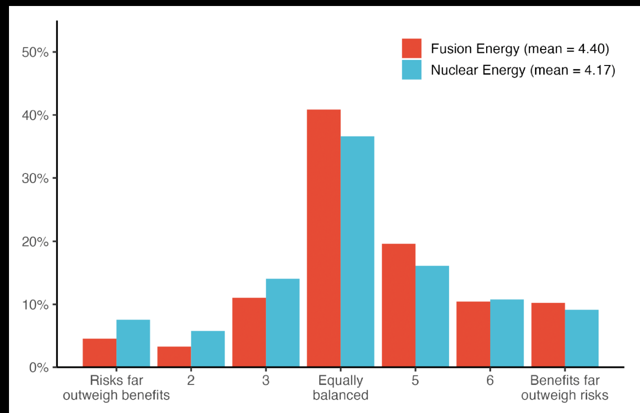
Public Perception of Nuclear Technology

Kuhika Gupta
Associate Director
Institute for Public Policy Research and Analysis
University of Oklahoma









The distribution of respondent perceptions about the risks and benefits of fusion energy and nuclear energy.

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Conclusions

Nuclear energy stands at a critical juncture.

The challenges of safety, waste management, and cost must be addressed for the industry to flourish in the future.

The rise of advanced reactor designs, fusion research, renewed focus on decarbonization and public perception signal a potential new era for nuclear energy, where it could play a vital role in providing clean and reliable power as part of a diversified energy mix

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