ADVANCED REACTORS

WHAT THEY ARE AND WHY WE NEED THEM TO SAVE OUR PLANET

November 23, 2020

by Richard Steeves, MD PhD

26 low carbon energy sources shut-down in 3 years, under the pressure of anti-nuclear actions

UNITED STATES

3 reactors (2,5 GW)
- Pilgrim 1 $
- Three Miles Island 1
- Indian Point 2 $

3 reactors (2,5 GW)
- Duane Arnold
- Indian Point 3
- Palisades

ASIA

7 reactors (6GW)
- Chinshan 2 (Taïwan)
- Genkai 2 (Japan)
- Fukushima Daini 1, 2, 3, 4 (Japan)
- Wolsong 1 (South Korea) $

● reactor shut-down
● planned shut-down of reactor
political reason
$ economical reason

EUROPE

4 reactors (3,5 GW)
- Muehleberg (Switzerland)
- Ringhals 2 (Sweden)
- Philippsburg 2 (Germany)
- Fessenheim 1 (France)

9 reactors (10,8 GW)
- Fessenheim 2 (France)
- Ringhals 1 (Sweden)
- Gundremmingen C (Germany)
- Grohnde (Germany)
- Brokdorf (Germany)
- Doel 3 (Belgium)
- Isar 2 (Germany)
- Emsland (Germany)
- Neckarwestheim 2 (Germany)

Voices of Nuclear

WHY DOES THE MEDIA IGNORE NUCLEAR?

Environmental & Economic Benefits

$12 BILLION
In local, state and federal taxes paid annually

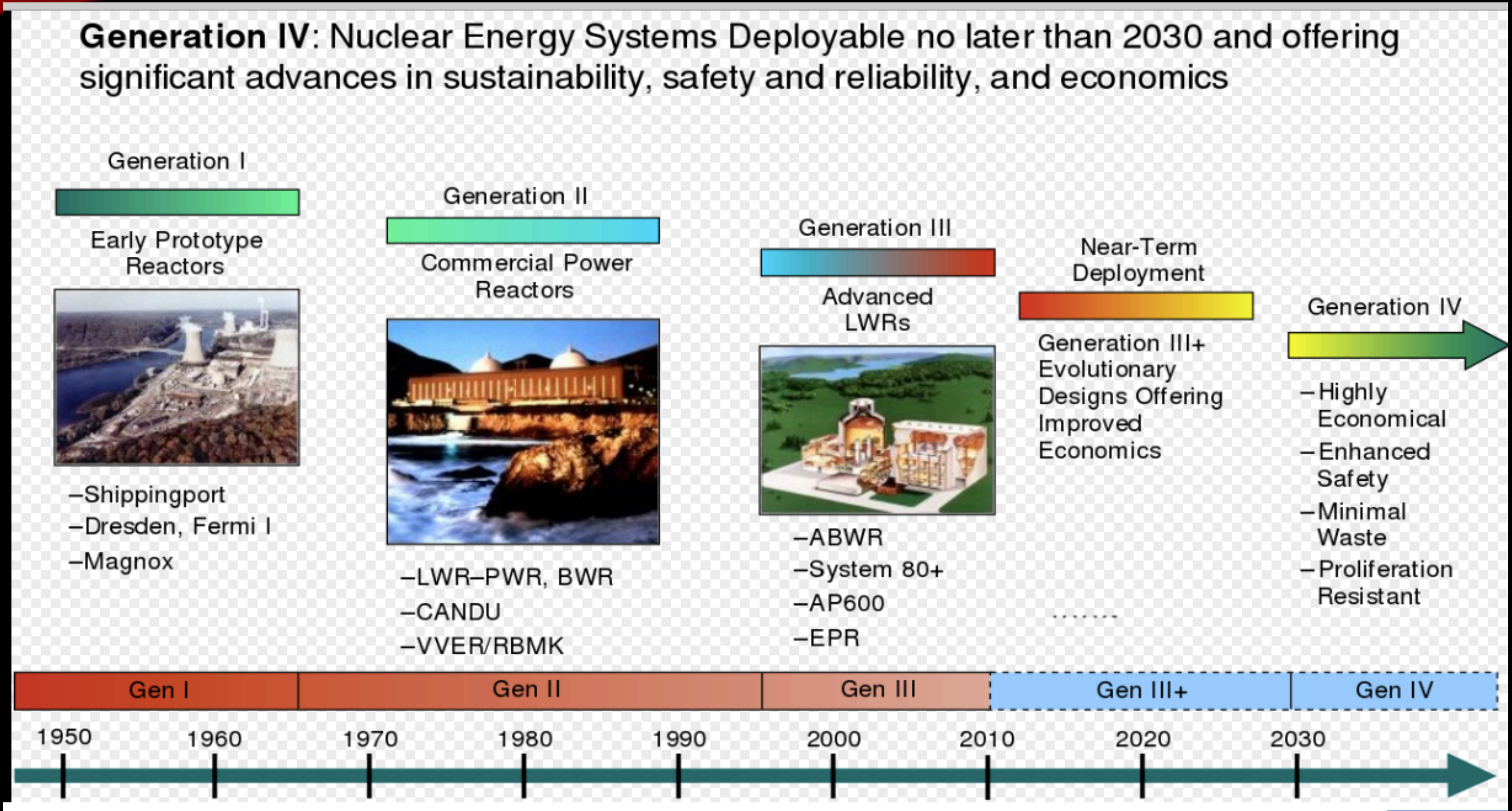
$470 MILLION
Revenue from plants buying local goods & services

500-900 WORKERS
Employed in each plant, earning wages nearly 36% higher than average

CARBON-FREE
Nearly 55% of all carbon-free electricity in the U.S. comes from nuclear

HEALTH & ENVIRONMENTAL BENEFITS
Studies show that when plants close, environmental, health and economic benefits are lost.

REACTOR EVOLUTION UP TO GEN IV



OLD-FASHIONED LWR (VOGTLE)

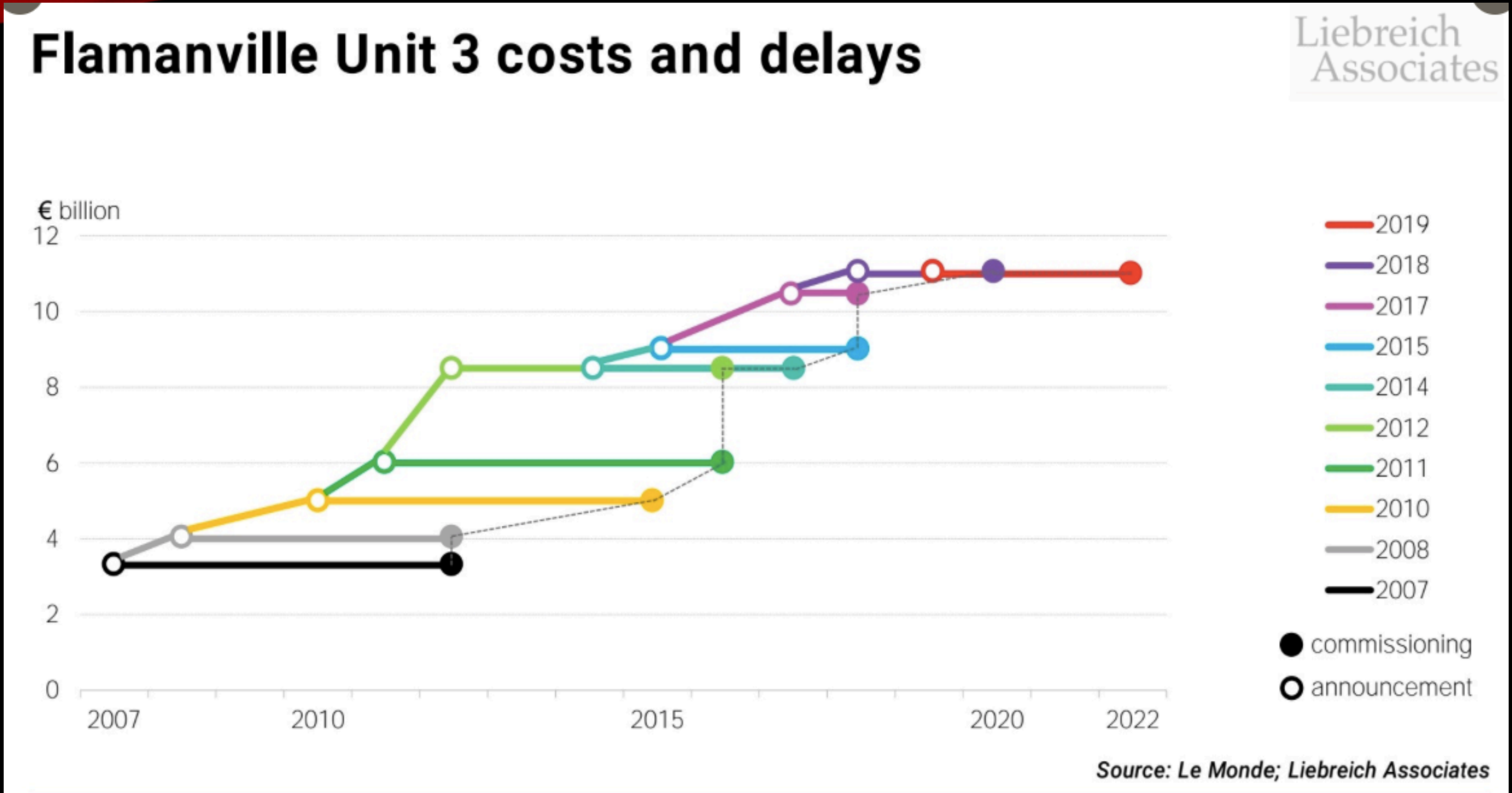
- These huge Gen-III LWRs are NOT "ADVANCED", because they are:
- Anachronistic in design (1943).
- Land-print is too large.
- Expensive, over-engineered for safety, post-Fukushima.
- Fuel utilization is low (1 – 2 %).
- Too much reliance on specialized equipment and skills.

EUROPEAN PRESSURIZED REACTOR (EPR)

- EPRs (Gen III) - designed by a consortium: - Areva/EDF/Siemens - ~ in early 2000's; some are running; others still building in China, UK, India, Belarus.
- Many were cancelled or delayed (in Canada, Czech Rep., Finland, Italy, UAE, USA) after Fukushima (3/2011).
- France (Flamanville), Finland (Olkiluoto), England (Hinkley Point)



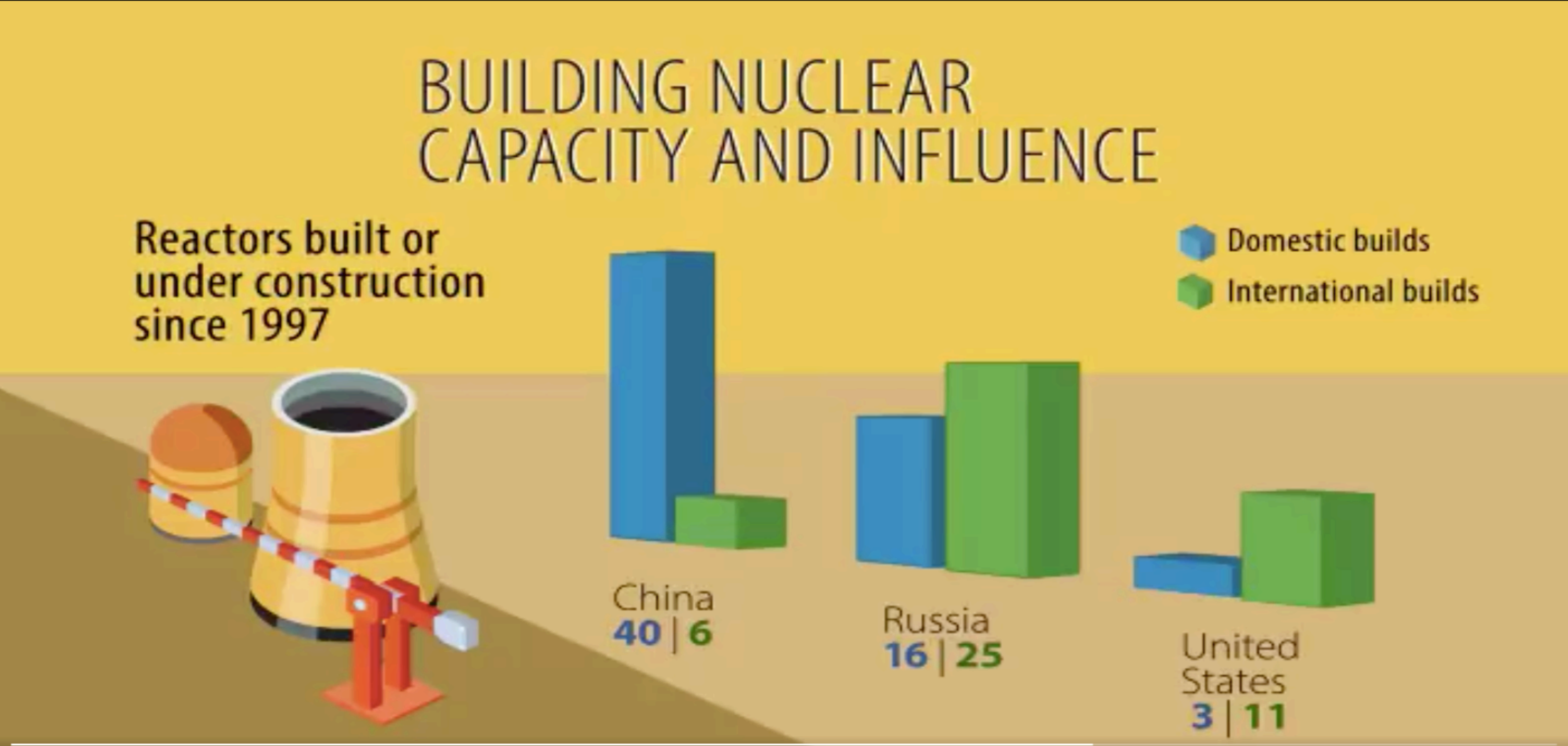
A BIG NUCLEAR NEGATIVE (GEN 3)



NEW GEN III REACTOR IN BELARUS

- Belarus' 1st plant has two Russian 1194 MWe units, to provide 1/3rd of their electricity.

SO….HOW DOES USA COMPARE ?

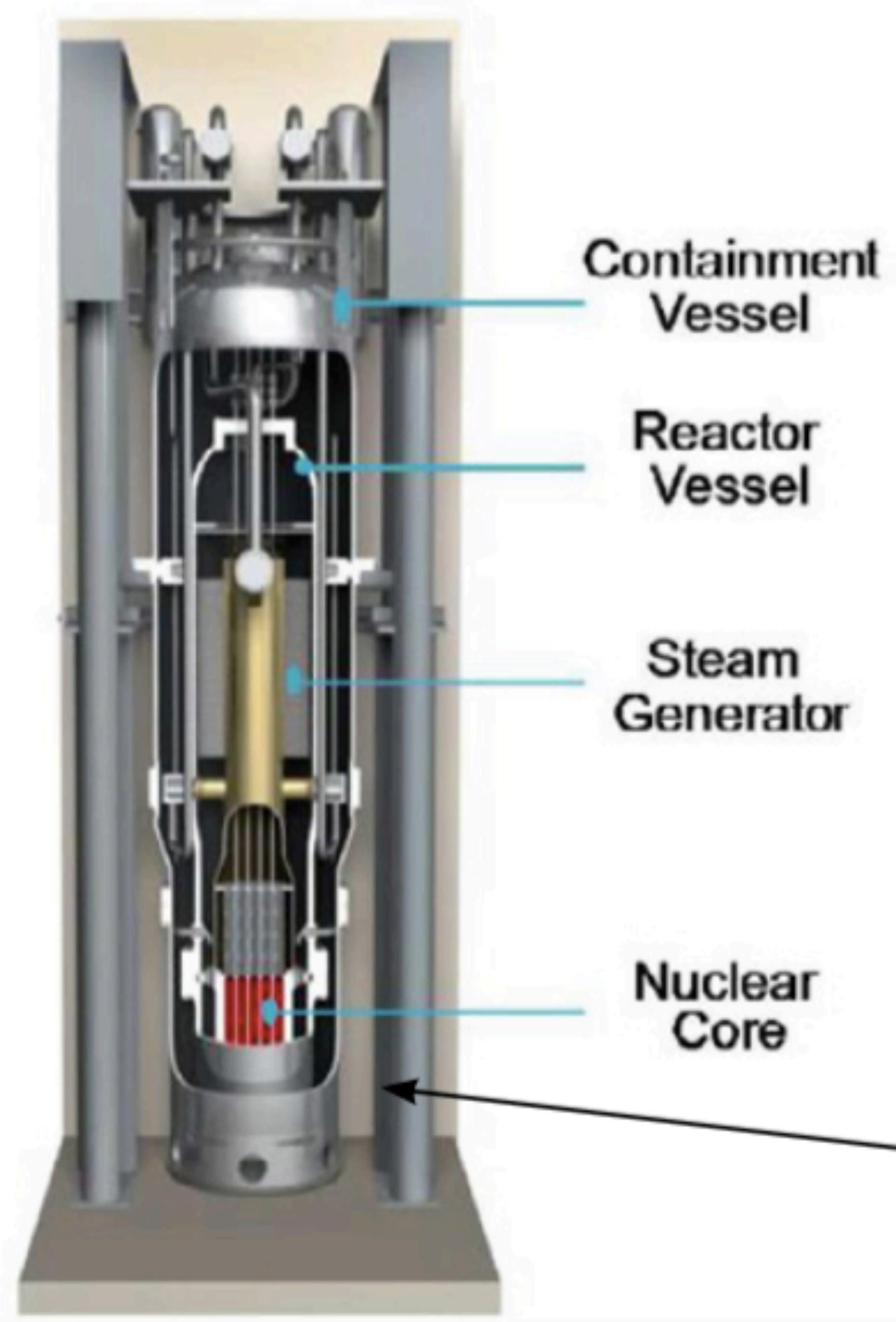


NEEDED NOW: **SMALL MODULAR REACTORS** (SMRs)

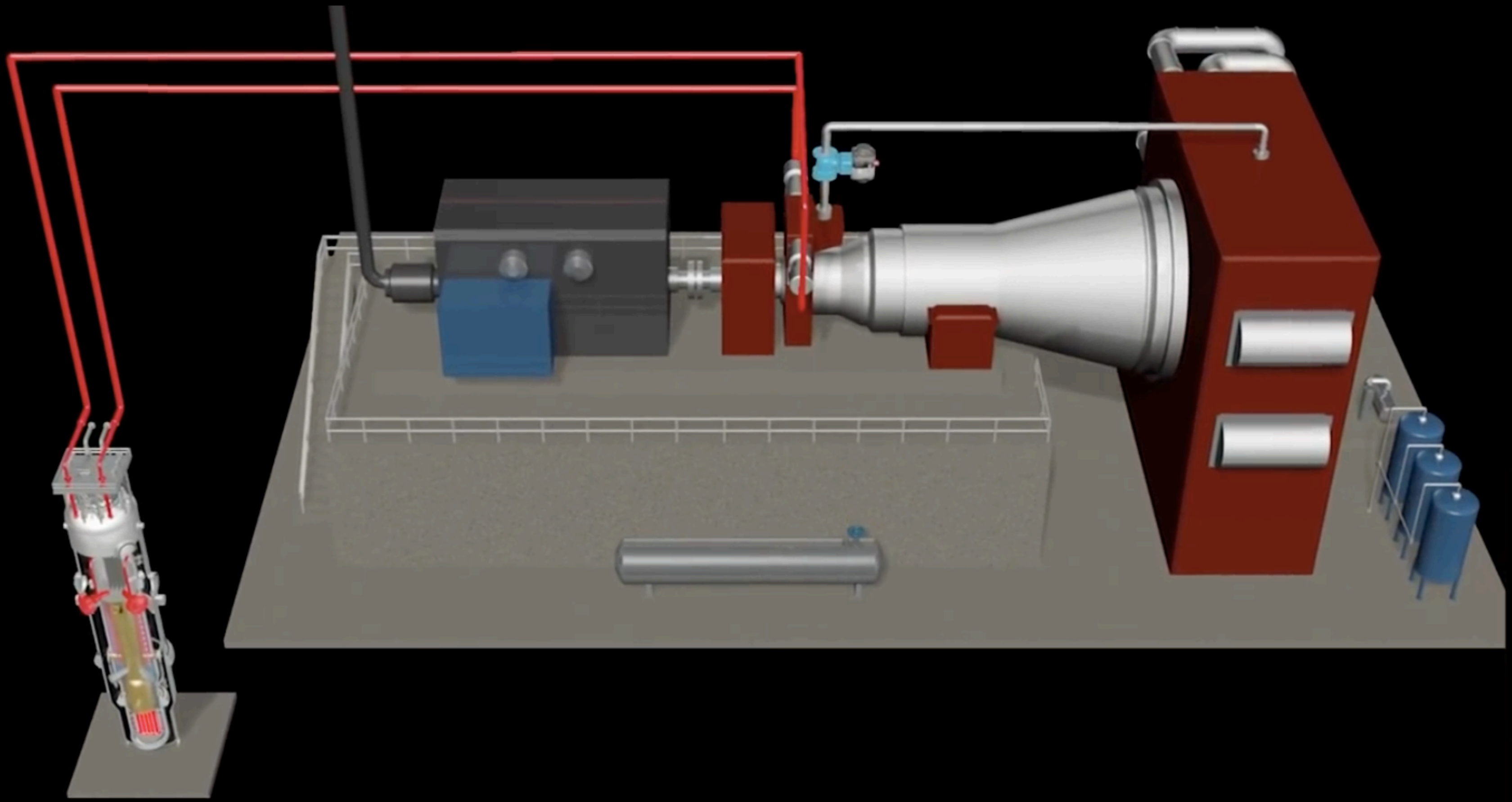
- An SMR's operation can be based on Gen II, or IV technologies.
- So, …. what characterizes an SMR? (Most of them generate < 300 MWe.)
- 1) it can run independently without active cooling (or offsite power)
- 2) it is small enough to have the entire reactor module fabricated at a central facility, and to be shipped on a rail car or by truck to the site for final assembly.

SMR = SIZE OF 2 SCHOOL BUSES STACKED UPRIGHT

- SMRs are <u>small</u>, scaled to fit the need, such as replacing a coal plant or for providing power in remote areas.
- SMRs are <u>modular</u>, able to be mass-produced off-site, then transported & attached to a steam plant.
- SMRs cool themselves by natural convection, without needing pumps.



THE TURBINE REMAINS ON THE SURFACE….

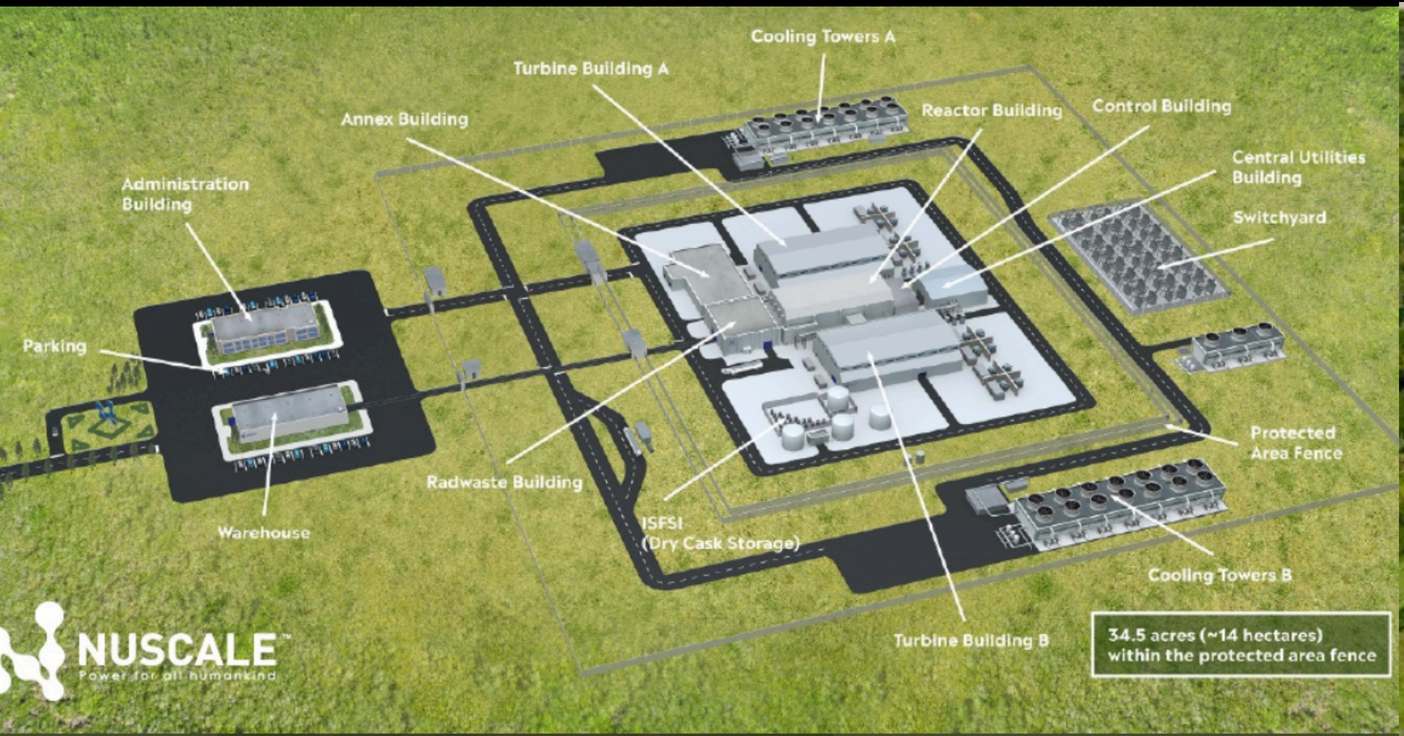


- Steam from the reactor (red line) drives the turbine (at right), which also drives the generator (center) and feeds the GRID.

12 NUSCALE SMR REACTORS CAN FIT HERE

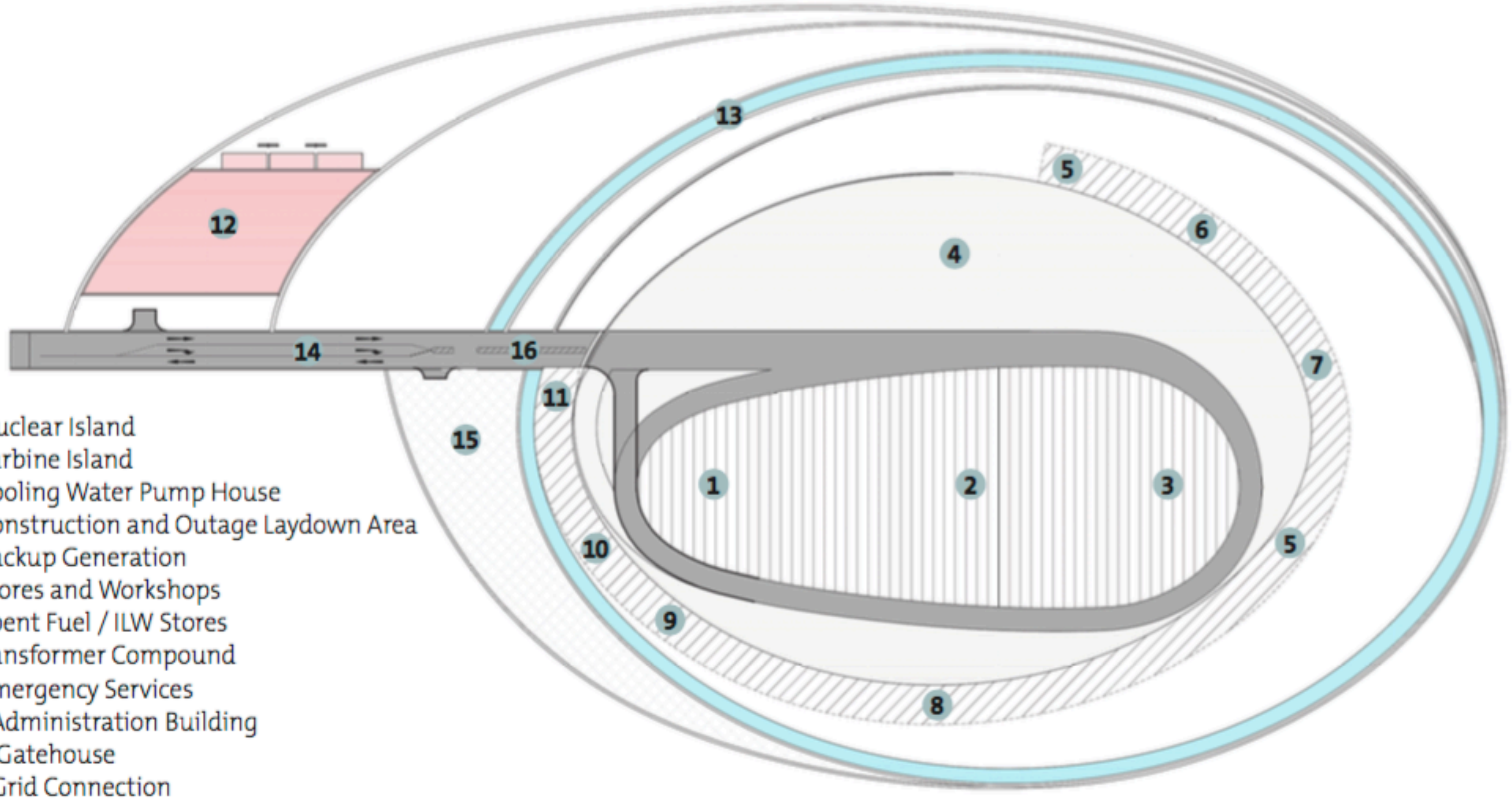
ENGINEER'S DRAWING

ARTIST'S SKETCH



FANCY SMR DESIGN BY ROLLS ROYCE

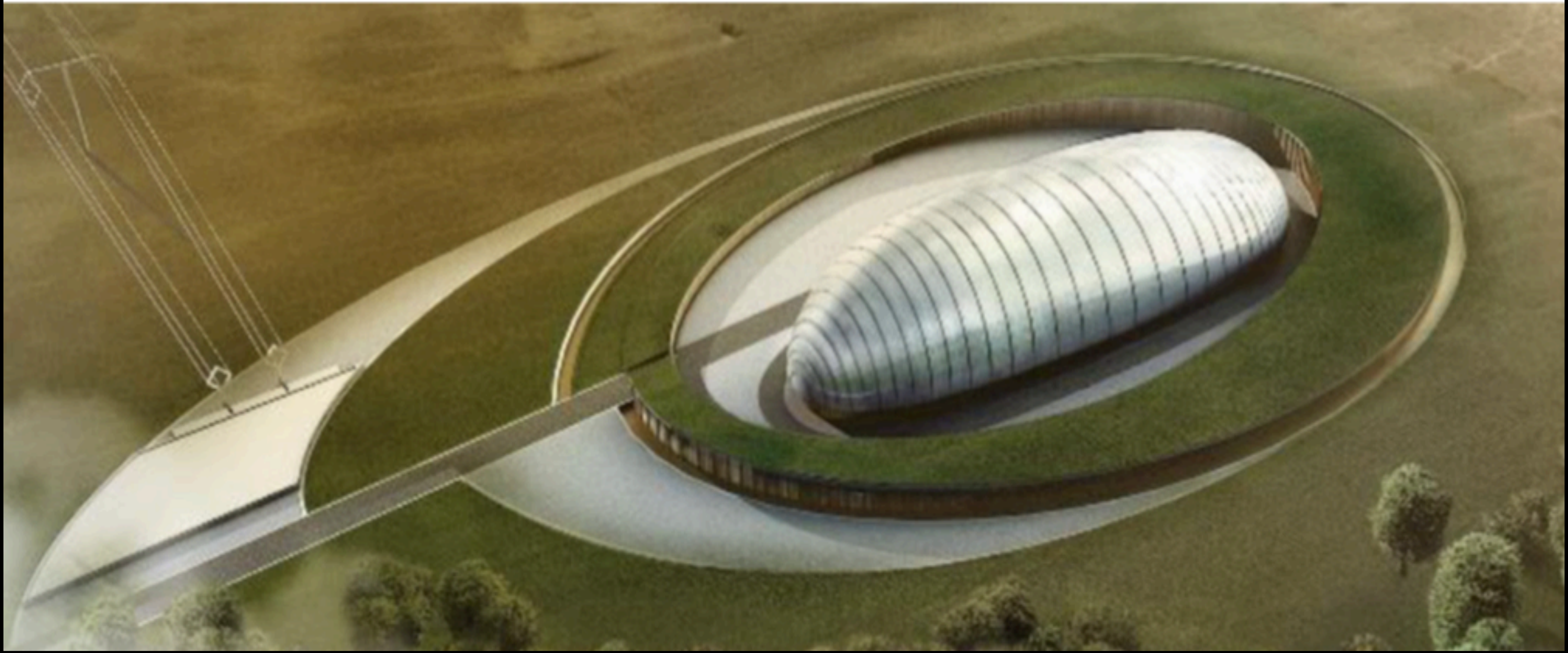
- Functional plan explains unusual shape with small footprint and pastoral setting.
- Output:400 Mwe.



1 - Nuclear Island
2 - Turbine Island
3 - Cooling Water Pump House
4 - Construction and Outage Laydown Area
5 - Backup Generation
6 - Stores and Workshops
7 - Spent Fuel / ILW Stores
8 -Transformer Compound
9 - Emergency Services
10 - Administration Building
11 – Gatehouse
12 - Grid Connection
13 - Security Barrier
14 - Road
15 - Car Park
16 - Site Access/Egress and Security Arrangement

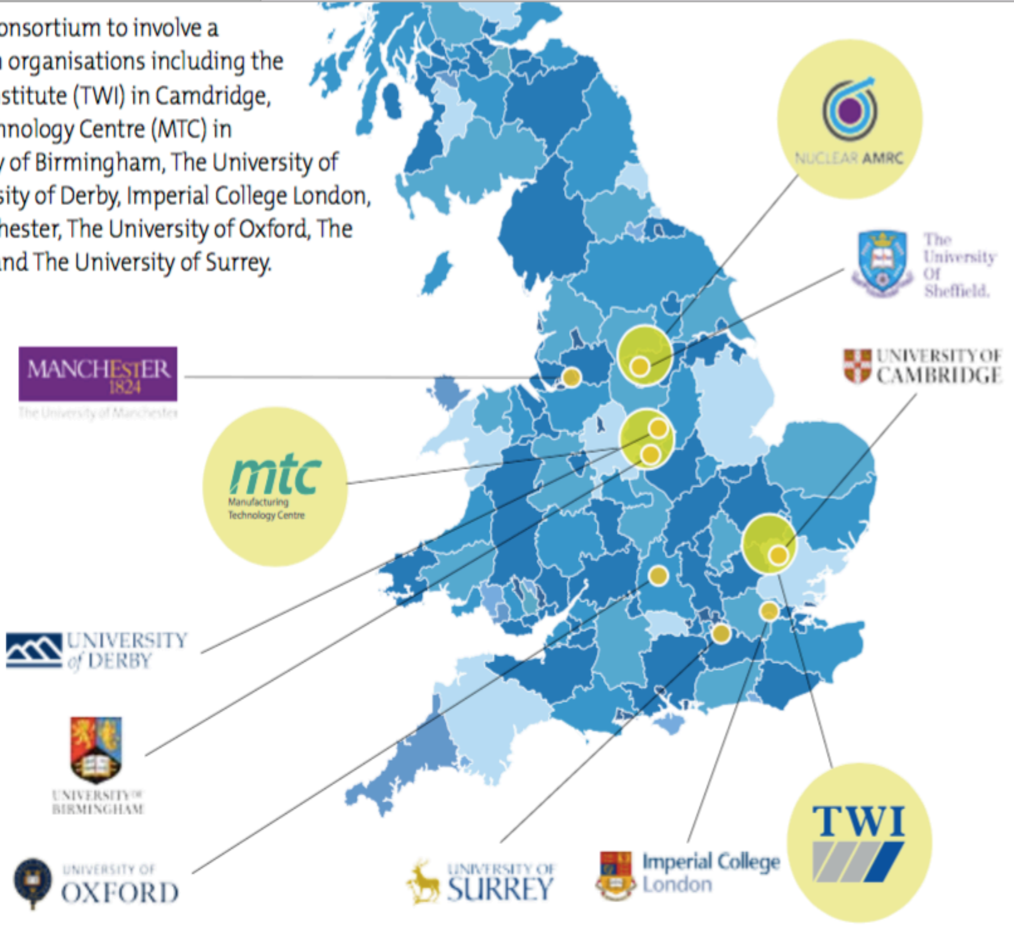
Figure 4 - UK SMR Plan Functional Arrangement

UK'S **ROLLS ROYCE** SMR OF THE FUTURE

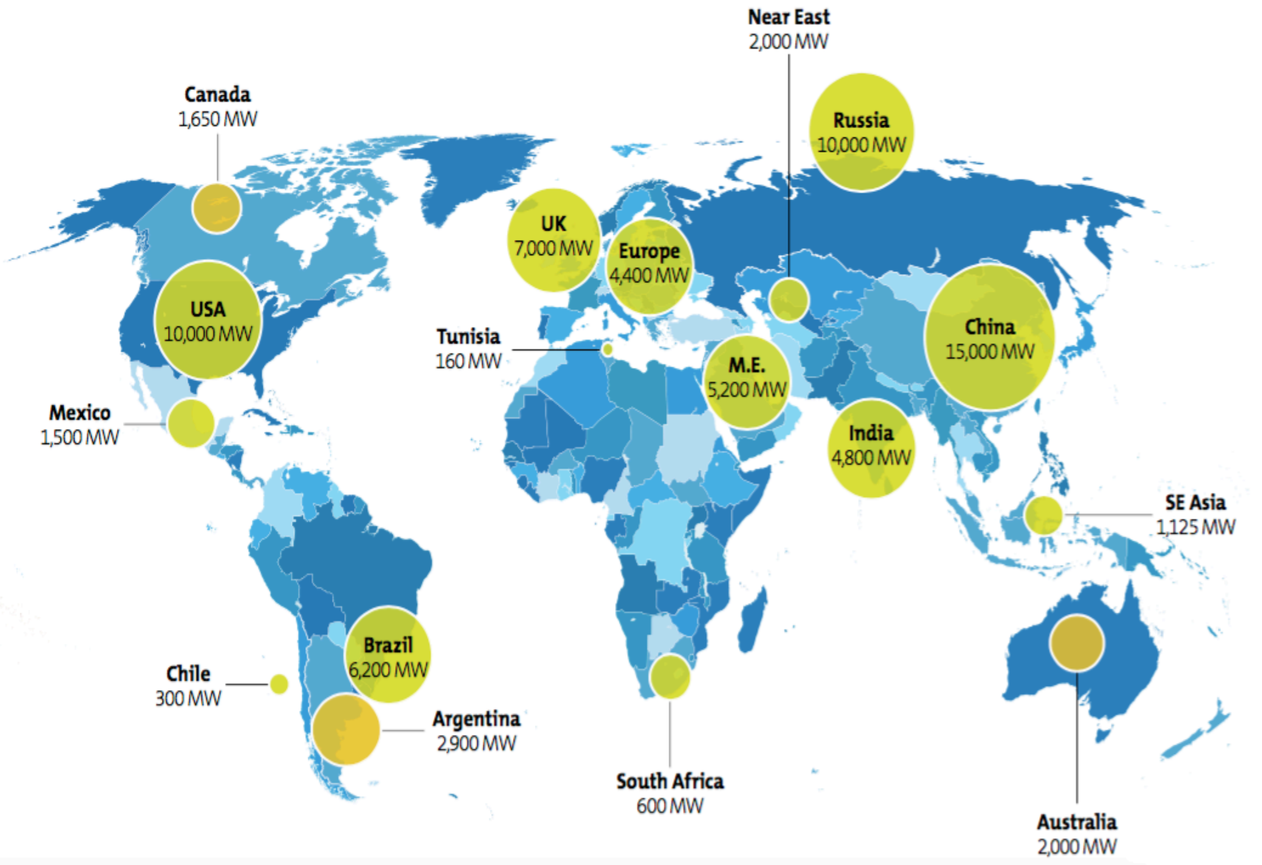


UK CONSORTIUM AND GLOBAL MARKETS

We would expect our Consortium to involve a broad range of research organisations including the NAMRC, The Welding Institute (TWI) in Camdridge, the Manufacturing Technology Centre (MTC) in Coventry, The University of Birmingham, The University of Cambridge, The University of Derby, Imperial College London, The University of Manchester, The University of Oxford, The University of Sheffield and The University of Surrey.



The size of the potential global SMR market, is approximately 65-85GW by 2035, valued at £250-£400bn.



UK PROJECTED ENERGY PROFILE

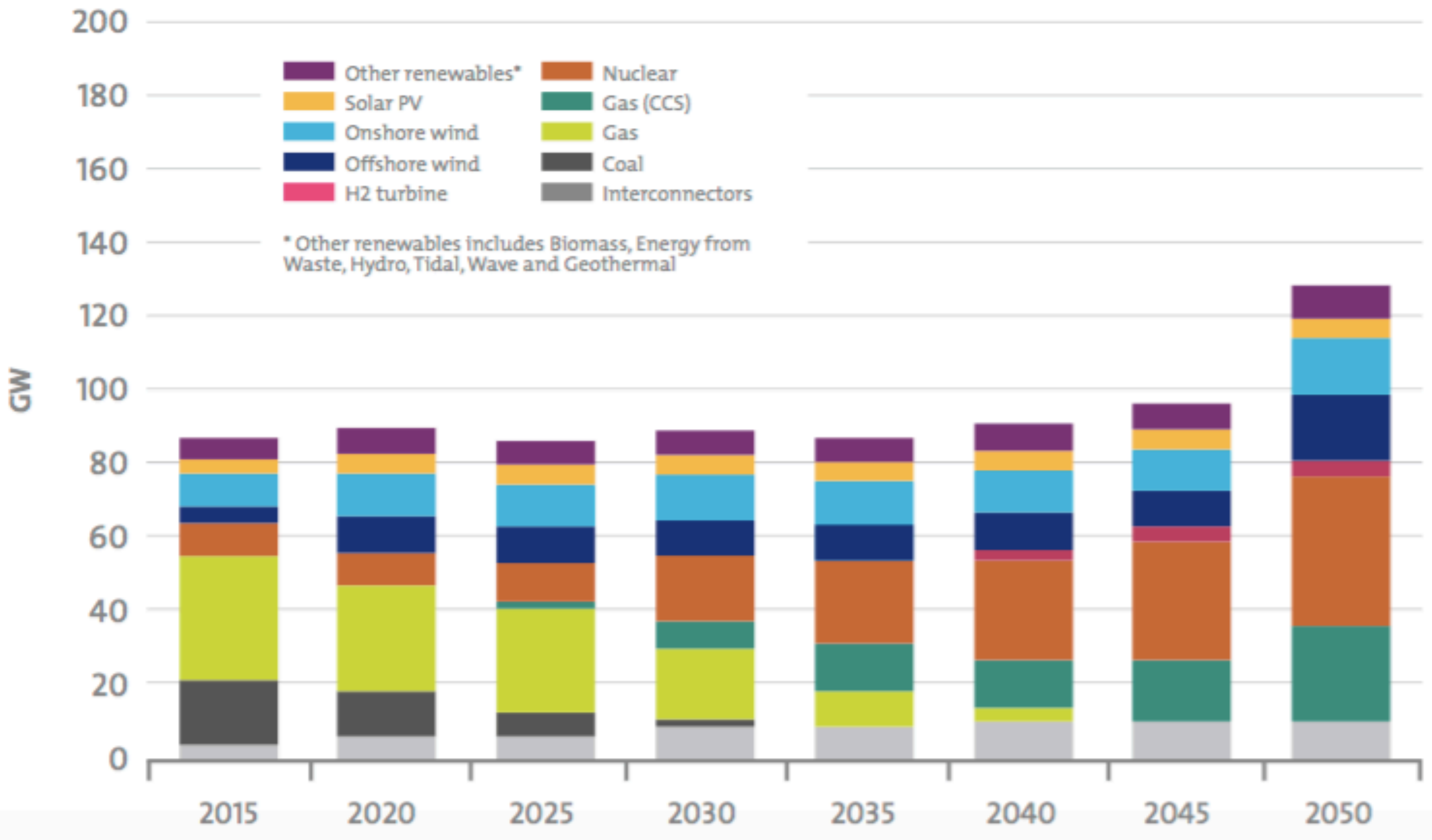


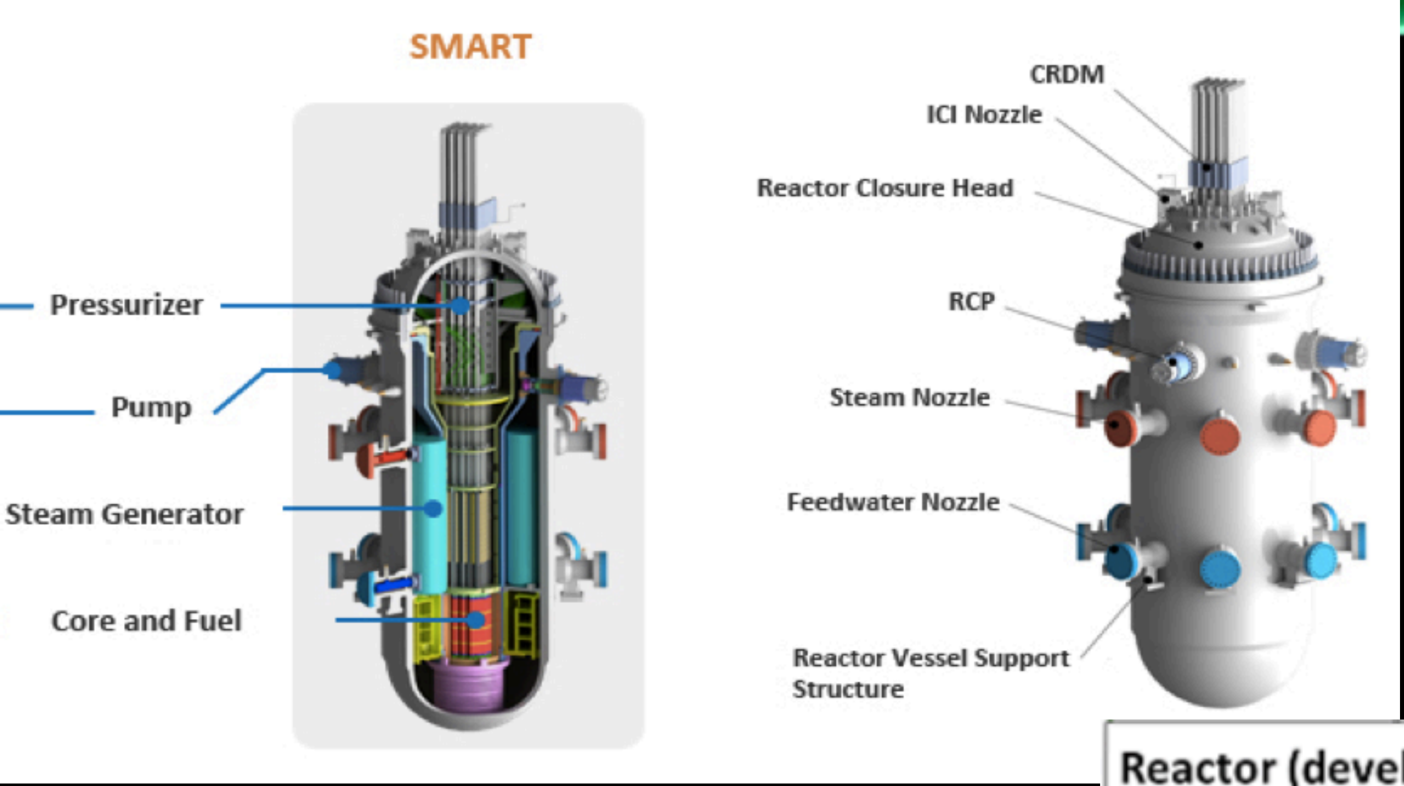
Figure 1. ETI 'Clockwork' scenario; showing rise of nuclear from current levels to around 40 GWe by 2050 (ETI, 2015)[10].

FLOATING SMR IN RUSSIAN ARCTIC

- This floating modular reactor provides power for up to 200,000 people in Murmansk.
- Fueled every 5 years, its 2 KLT water-cooled reactors make 70 MWe, (300 MW of heat) and should last ~ 40 years.
- For now it is the first operating SMR, & the first floating atomic power plant in the Arctic.

Akademik Lomonosov is a floating nuclear power plant with 70MW of installed capacity. Image courtesy of Alex Bakharev.

KOREA'S KAERI SMR IS SMART &POPULAR, AMONG OTHERS…



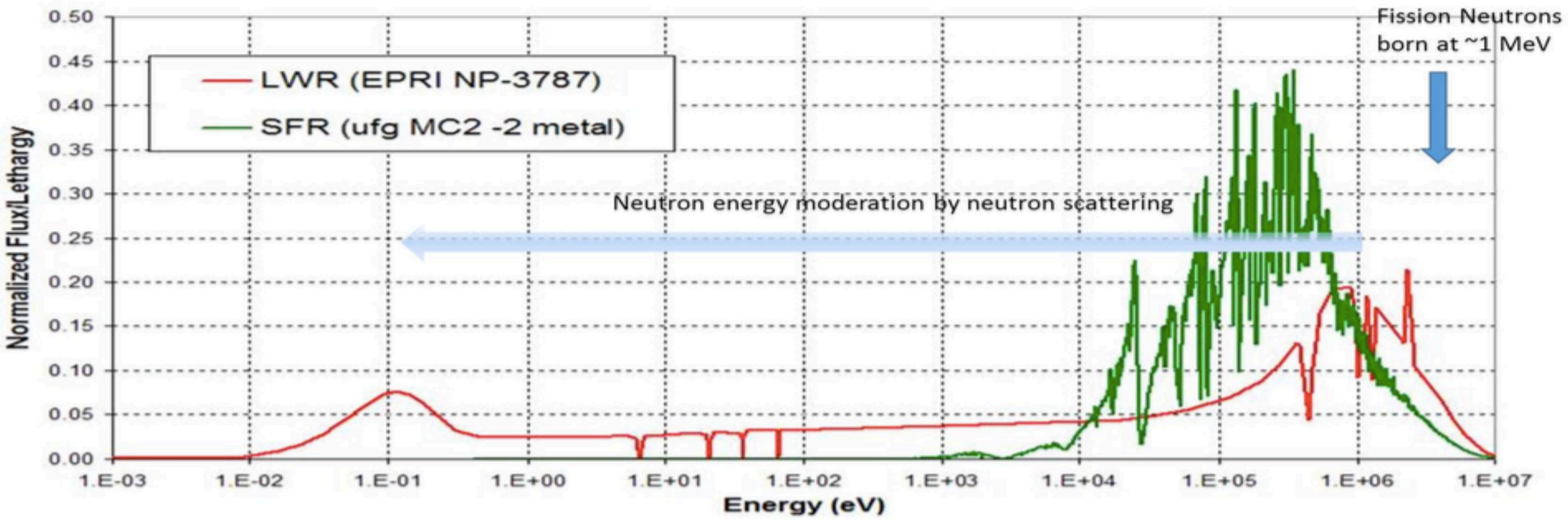
Reactor (developer/vendor)	Type, capacity thermal/electric, MW	Status
mPower (B&W + Bechtel)	PWR, 530 / 180	near future
W-SMR (Westinghouse)	PWR, 800 / 225	near future(?)
SMR-160 (Holtec Int)	PWR, 446 / 160	near future
NuScale (NuScale + Fluor)	PWR 160 / 45	near future
Floating NPP (Afrikantov Inst.)	PWR, 150 / 38	in build
ACP100 (CNNC)	PWR, 385 / 120	planned
SMART (KAERI)	PWR, 330 / 100	near future
CAREM (CNEA, INVAP)	PWR, 100 / 27	in build
Flexblue (AREVA, DCNS)	PWR, n.d. a. / 50-250	near future(?)

GEN IV: **ENRICO FERMI** (L) & **WALTER ZINN** (R)

- Walter Zinn was a Canadian émigré, naturalized as a U.S. citizen in 1938. He came from Columbia U to Chicago with Fermi in 1942, and was soon seen as a model for directing the building and operation of the EBR-1.
- Zinn's EBR-1 became the workhorse (for decades) for studying the effects of radiation on all kinds of materials.

WHY **SODIUM FAST REACTORS** (SFRs) ARE MORE EFFICIENT THAN **LWRs**

Fast Neutrons



- **In LWRs, most fissions occur in the ~0.1 eV "thermal" peak**
- **In SFRs, neutron energy moderation is avoided – fission in "fast" energy range**

Comparison of LWR and SFR (1/2)

	LWR	SFR
Core and Fuel	• Thermal neutron system • Lower fissile density • Lower fuel burn up	• Fast neutron system • Higher fissile density • Higher fuel burn up
Coolant	• Water ✓ Lower thermal conductivity ✓ Lower boiling point ◆ 100 deg C at atmospheric pressure ◆ 345 deg C at 16 MPa	• Sodium ✓ Higher thermal conductivity ✓ Higher boiling point ◆ 883 deg C at atmospheric pressure ✓ Higher chemical reactivity
System pressure	• High (7 to 16 MPa)	Nearly atmospheric pressure
Environment	• Lower temperature (30 to 350 deg C) • Thermal neutron • Water	• Higher temperature (300 to 600 deg C) • Fast neutron • Sodium

GLOBAL HISTORY OF 25 FAST, GEN IV REACTORS USED OVER 400 OPERATING YEARS

International Fast Reactors

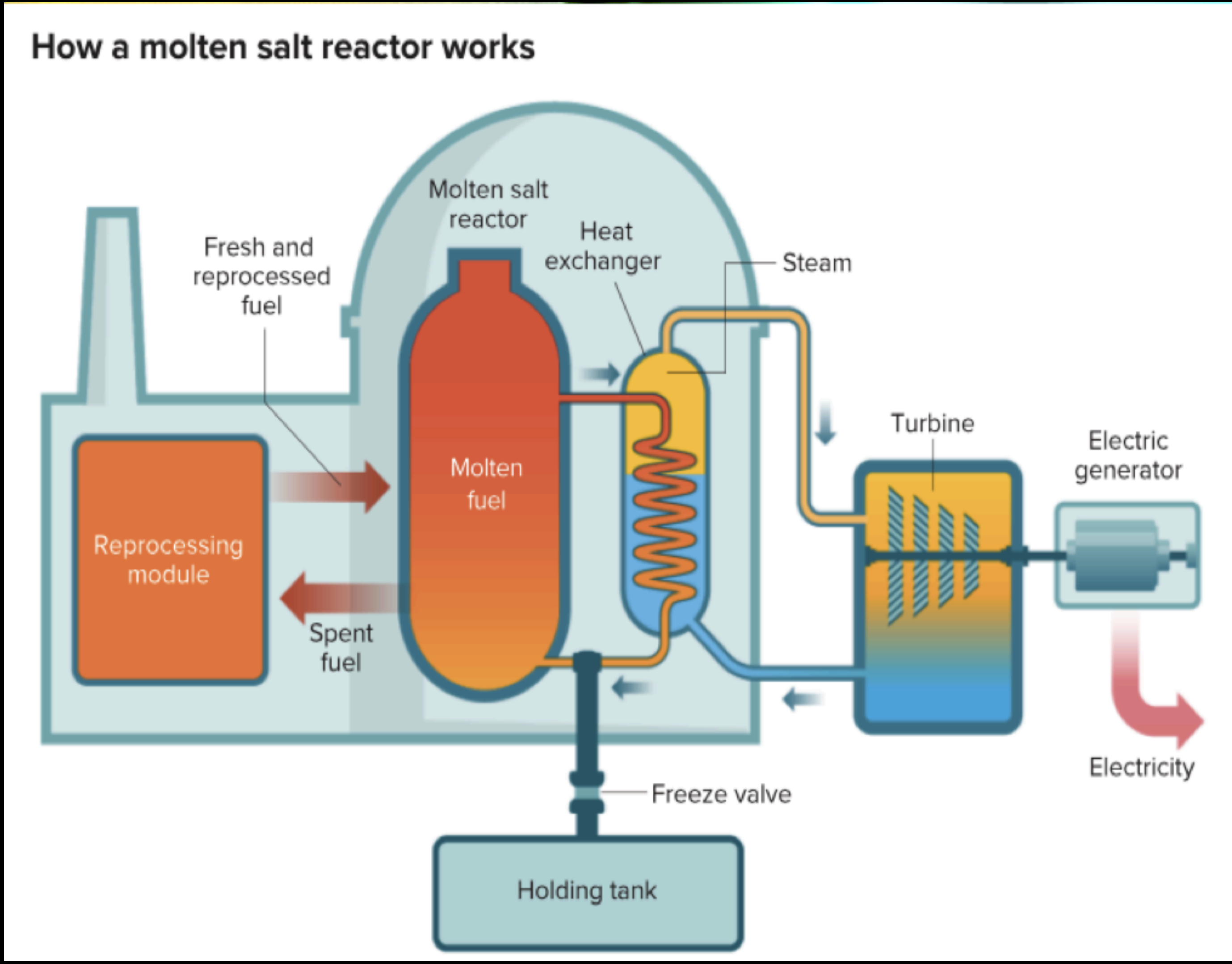
Reactor	Country	MWth	Operation	Coolant
EBR 1	USA	1.4	1951-63	NaK
BR-2	Russia	2	1956-1957	Mercury
BR-10	Russia	8	1959-71, 1973-2002	Sodium
DFR	UK	60	1959-77	NaK
EBR II	USA	62.5	1963-94	Sodium
Fermi 1	USA	200	1963-72	Sodium
Rapsodie	France	40	1966-82	Sodium
BOR-60	Russia	50	1968-	Sodium
SEFOR	USA	20	1969-1972	Sodium
OK-550/BM-40A	Russia	155 (7 subs)	1969-	Lead Bismuth
BN 350*	Kazakhstan	750	1972-99	Sodium
Phenix	France	563	1973-2009	Sodium
PFR	UK	650	1974-94	Sodium
KNK 2	Germany	58	1977-91	Sodium
Joyo	Japan	140	1978-	Sodium
FFTF	USA	400	1980-93	Sodium
BN 600	Russia'	1470	1980-	Sodium
Superphenix	France	3000	1985-98	Sodium
FBTR	India	40	1985-	Sodium
Monju	Japan	714	1994-96, 2010-	Sodium
CEFR	China	65	2010-	Sodium
PFBR	India	1250	2016?	Sodium
BN-800	Russia	2000	2014-	Sodium
ASTRID	France	1500	2025?	Sodium
PGSFR	Korea	400	2028	Sodium

GENERATION IV NUCLEAR SYSTEMS

System	Abbreviation	Neutron Spectrum	Coolant	Fuel Cycle	Size (Mwe)
Sodium Fast Reactor	SFR	FAST	Sodium	Closed	30 - 2000
Lead-cooled Fast Reactor	LFR	FAST	Lead (Bi)	Closed	20 - 1000
Gas-cooled Fast Reactor	GFR	FAST	Helium	Closed	1200
Molten Salt Reactor	MSR	Epithermal/Fast	Cl or F salts	Closed	1000
Super-critical Water-cooled Reactor	SCWR	Thermal/Fast	Water	Open/Closed	300 - 1500
Very High Temp. Reactor	VHTR	Thermal	Helium	Open	250

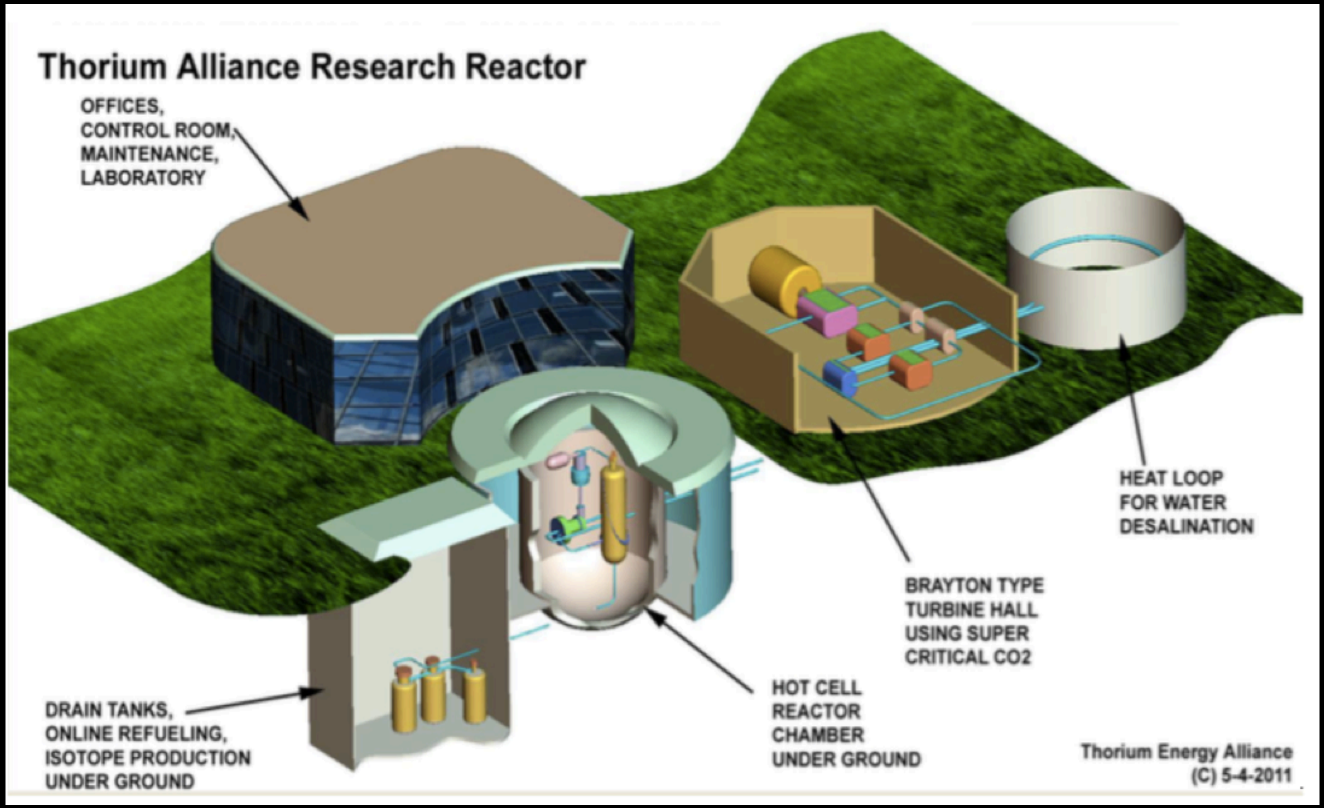
MOLTEN SALT REACTORS
DIFFER FROM OTHER FAST REACTORS BECAUSE THEY:

- 1. Use liquid fuel dissolved in molten salt, avoid complex fuel loading, and produce heat directly into transfer fluid.
- 2. Reprocess the fuel without having to shut down the reactor, and extract the fission products, so the original nuclides can be completely fissioned →
- 3. Have a holding tank under a freeze-valve in case of over-heating →



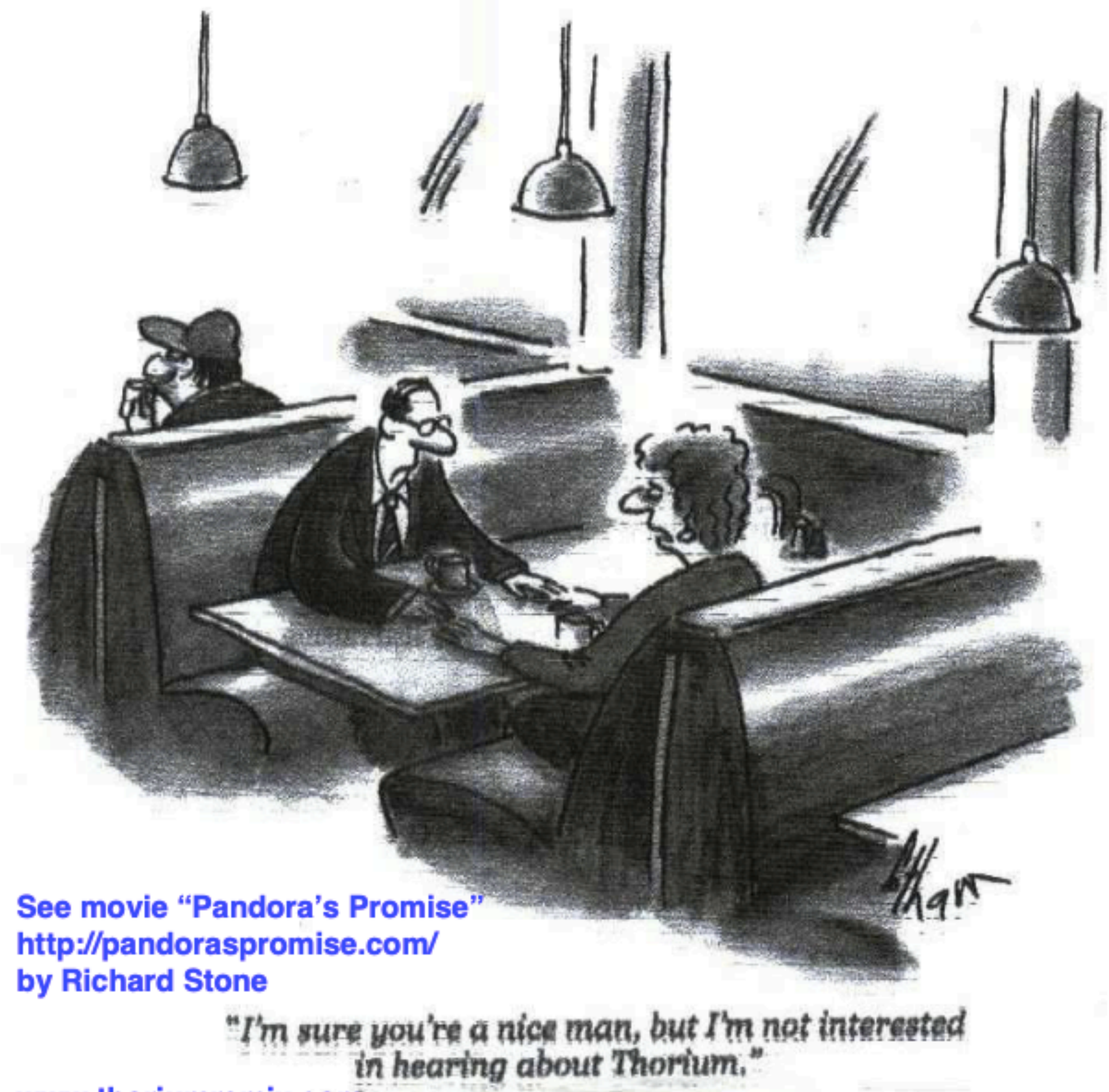
MSRs HAVE OTHER ADVANTAGES

- Typical waste from a 1000 MWe MSR over 30-years < 100 lb (1/2 sq. ft.).
- Plutonium waste is 1/1000th that of a comparable LWR (light water reactor).
- MSRs automatically ”throttle down” as atoms in fluid thermally expand.
- Thus, there cannot be a “meltdown”.
- Higher temps give ~30% better thermal efficiency without pressurization.
- MSRs can be fueled readily by thorium and/or uranium.



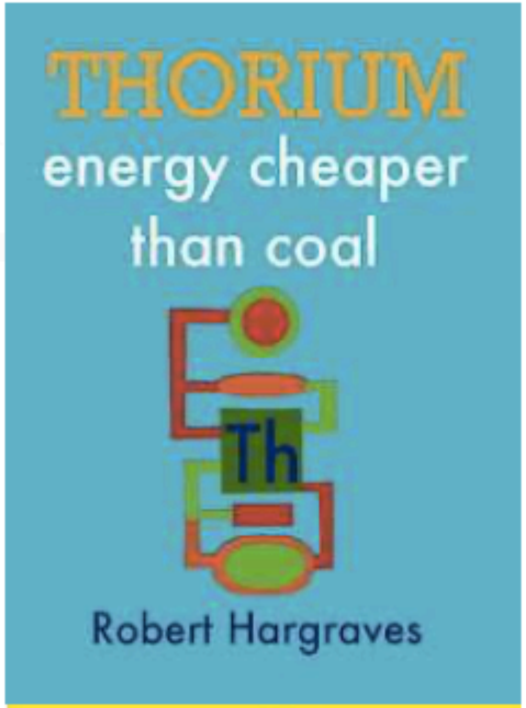
MSR COMPANIES IN N. AMERICA

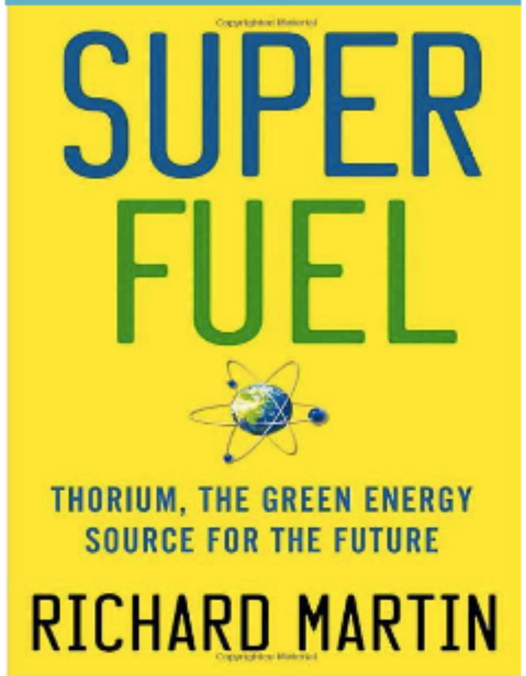
COMPANY NAME	LOCATION	LEADER	REMARKS
Terrestrial	Chalk River, Ontario	Simon Irish	Small modular design
TerraPower	Bellevue, WA	Bill Gates	Southern Company
Elysium	Schenectady, NY	Ed Phiel	Extensive experience
Thorcon Power	Stevenson, WA	Lars Jorgensen	Scalable, Thorium fuel
Moltex	St, John, Canada	Ian Scott	Thorium in Cl salt
Flibe	Huntsville, AL	Kirk Sorenson	Thorium in F-Be salt
AlphaTech	Salt Lake City, UT	Data requested	Micro-reactors too.



See movie "Pandora's Promise"
http://pandoraspromise.com/
by Richard Stone

www.thoriumremix,com
https://www.youtube.com/watch?v=nQpuGwWyFQ0





THORIUM IS THE FUEL.

MSR IS THE TOOL

NUCLEAR vs. RENEWABLES #1

- Power plants based on the fission of Uranium or Thorium generate power 24/7, and they last 3 - 4 times longer than solar or wind plants, which need battery backup.
- The space required to support nuclear plants are up to 100 times less than for solar and wind plants with battery backup.

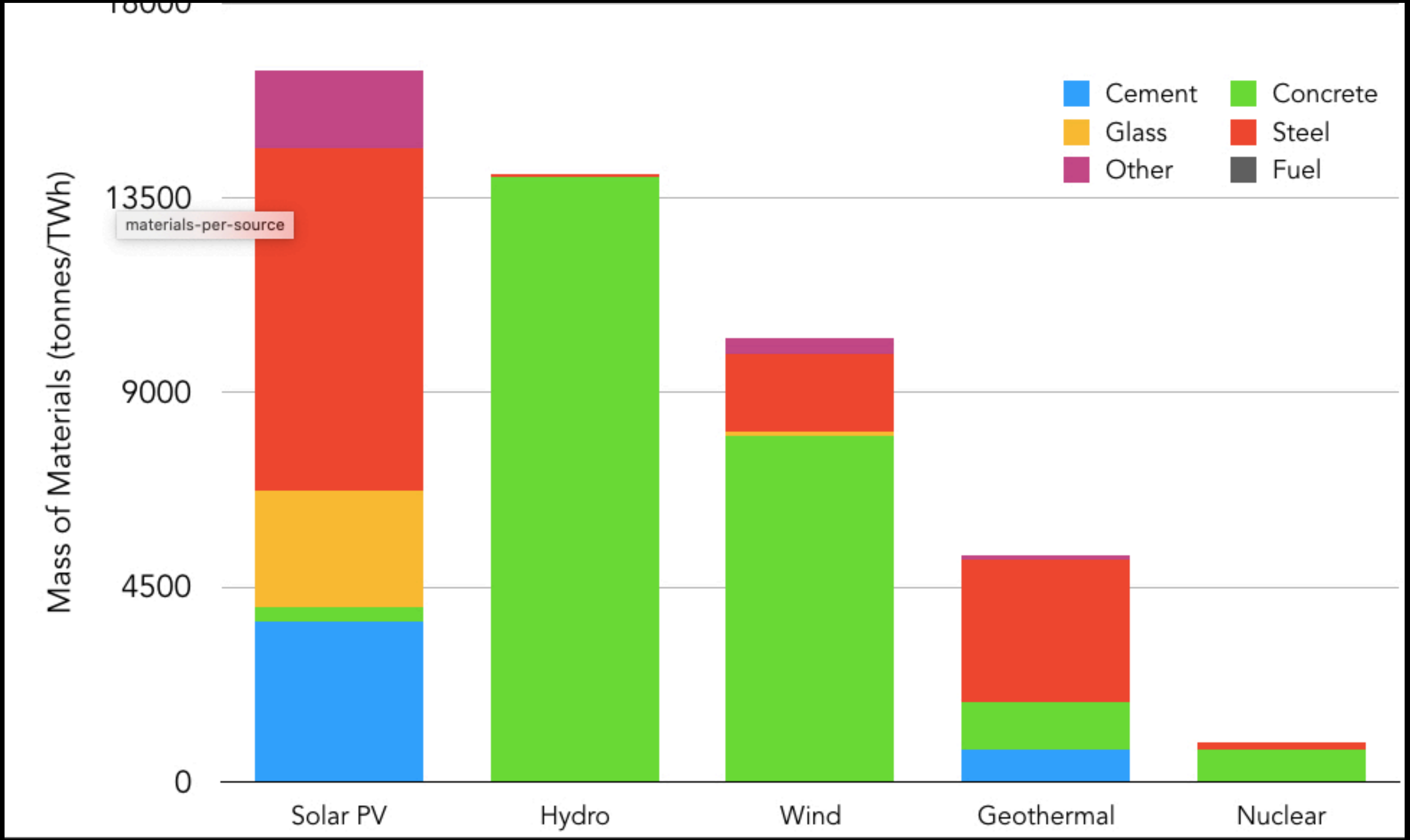
Technology	Capacity Factor, %	Square Miles Needed For 1000 MW
Wind	32-47	260-360
Solar	17-28	45-75
Nuclear	90	1.3

footprint

NUCLEAR vs. RENEWABLES #2

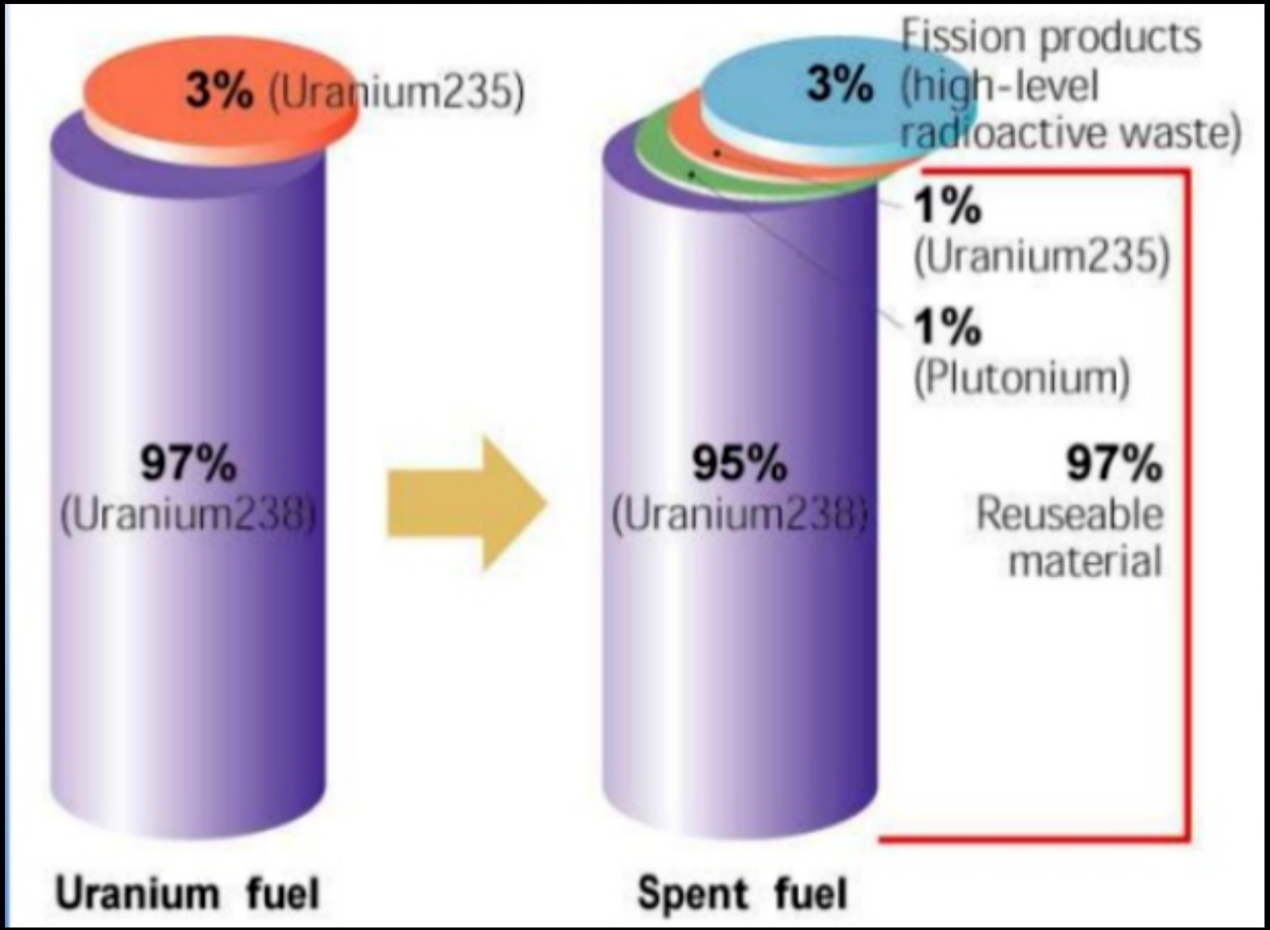
- Material Input, in terms of tonnes per TWh →

- Note that the low capacity factor for solar energy enlarges its relative consumption of cement and steel, compared with nuclear power.



NUCLEAR vs. RENEWABLES #3

- The entire US nuclear fleet has generated <80,000 tons of waste after 60 years, and most of the "waste" is spent fuel, ready to be consumed in Gen-4 reactors as soon as we start to make them, so mining will not be needed for >1000 years.
- The cost of nuclear power will become competitive with wind and solar power as soon as Gen-4 reactors are mass-produced in factories and assembled on site.

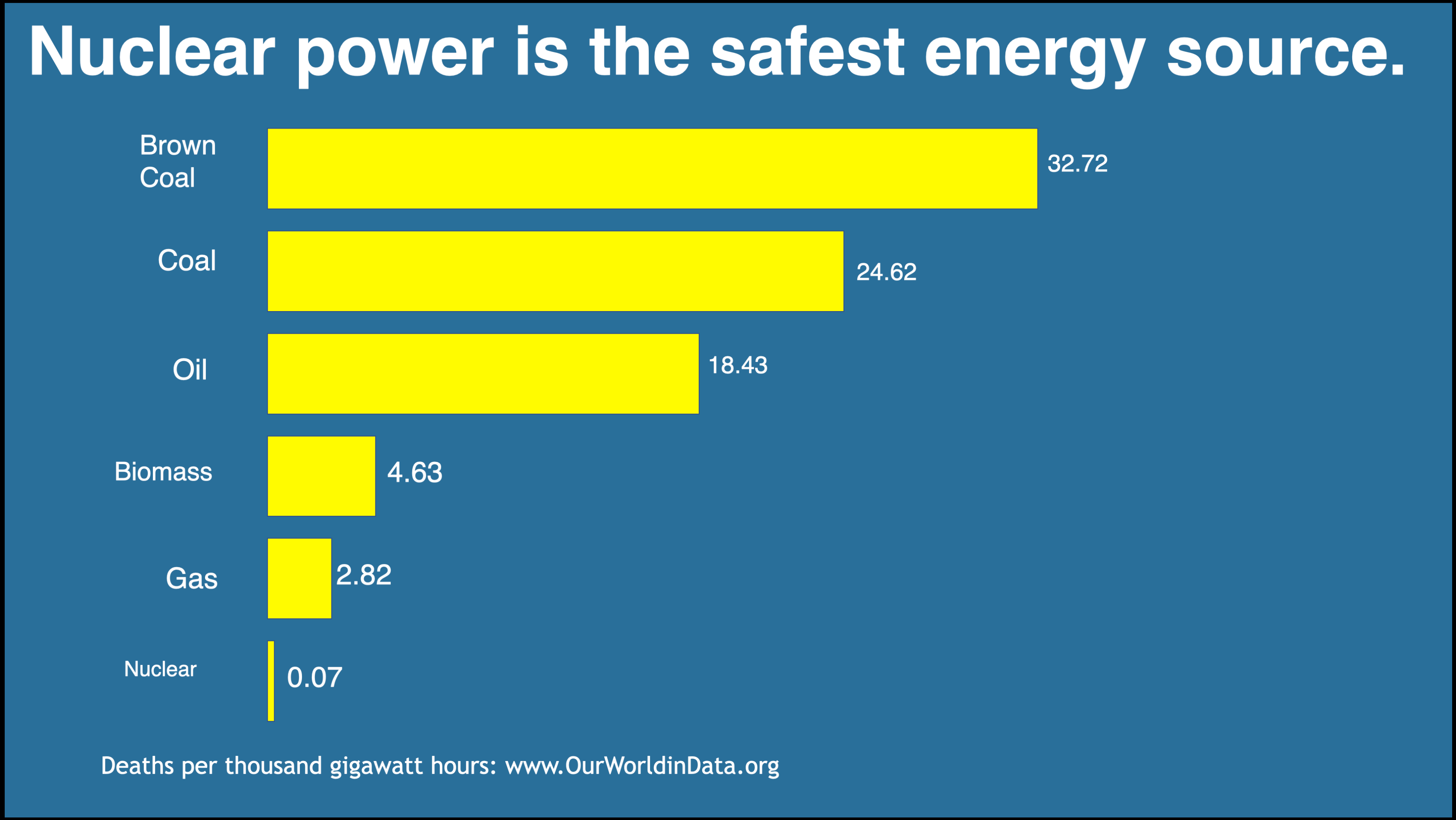


NUCLEAR vs. RENEWABLES #4

- As ground transportation switches from polluting gas & diesel to electricity, nuclear power will be needed to provide sufficient energy to leave coal and methane underground.
- Fission reactors will eventually power commercial shipping, and could be used to make hydrogen for hybrid power in commercial aircraft.

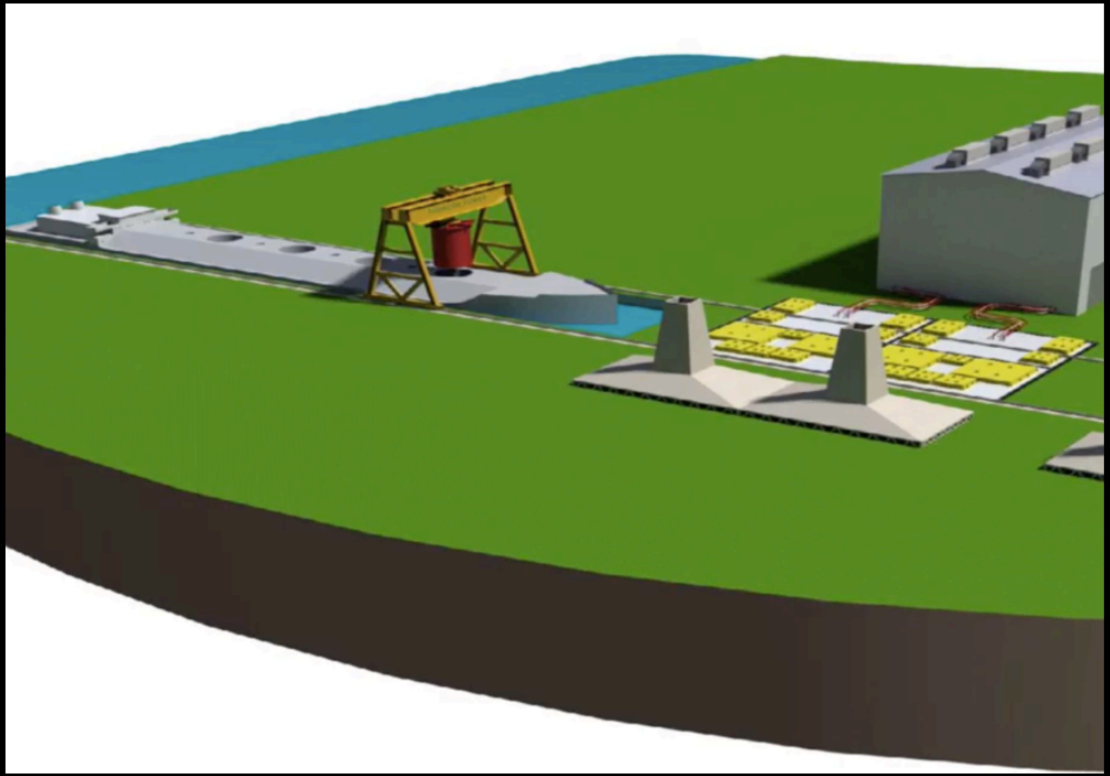
HOW CAN WE COMBAT FEAR?

- Fear dominates public opinion, based on poor understanding, and acceptance of green rhetoric that all will be fine with renewable energy alone.
- Big oil loves our ignorance.



TO SUMMARIZE: WHY AM I OPTIMISTIC?

- 1. NuScale, and other SMRs, now being approved by NRC, give a "time-bridge" until Gen-4 reactors are common.
- 2. Six different Gen-4 families give a multi-faceted approach.
- 3. The concept of floating reactors → (by Thorcon) is practical for Indonesia.
- 4. Fission power will reduce carbon emissions for transportation (maritime & rail) as well as making heat & electricity.
- 5. Gen-4 reactors consume old spent fuel, so we can forget about nuclear waste.



FISSION CAN HELP US SOLVE PROBLEMS

FOR MORE INFORMATION, TRY THIS: *RETHINKINGNUCLEAR.ORG*