Progress and Outlook for Advanced Nuclear

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EPRI Annual Seminar on Resource Planning for Electric Power Systems
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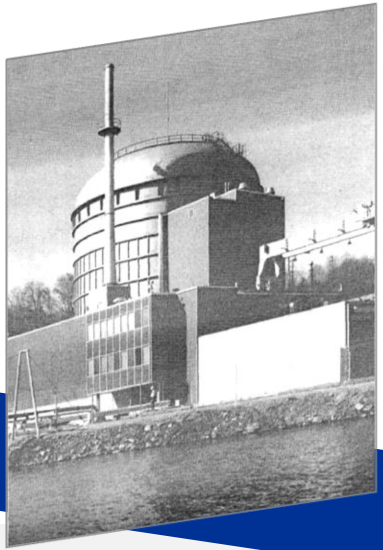
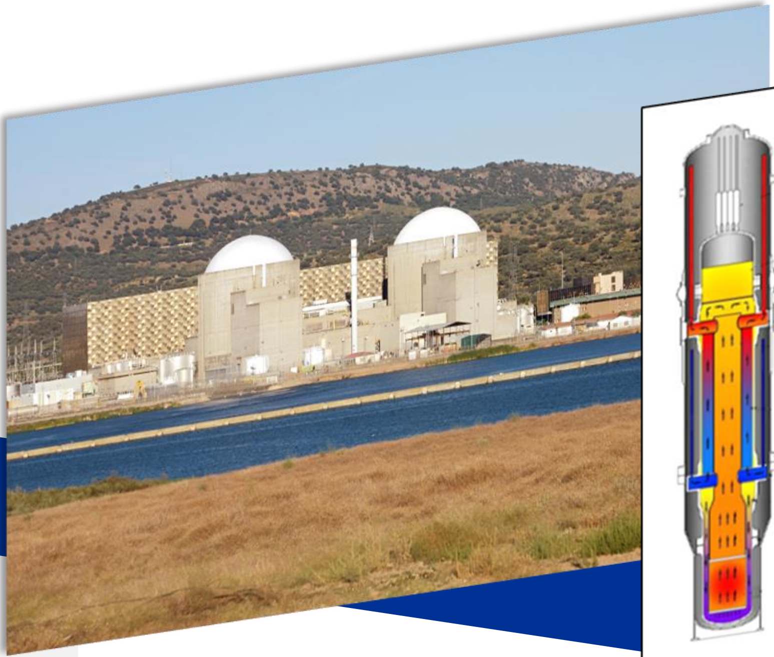
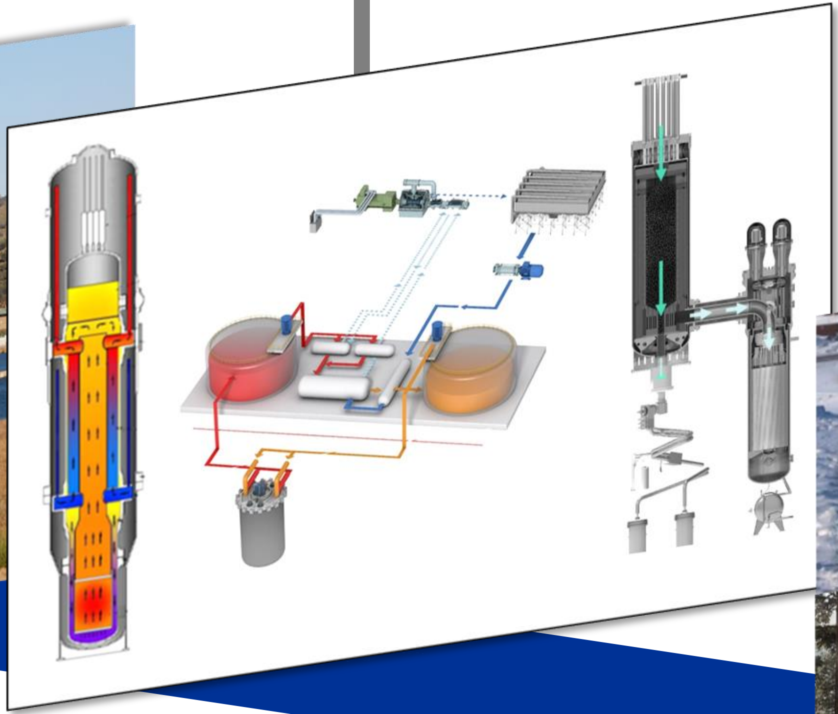
What is an Advanced Reactor?







GEN I & II

Early demonstrations through GW-scale commercial fleets

- Diversity of designs
- Diversity of vendors
- Diversity within vendors
- Limited standardization
- Aggressive build rates
- Evolving regulations

GEN III/III+

Evolutionary designs, GWe-scale +

- Convergence on ALWRs
- Passive safety
- Standardization
- Integration with licensing
- Emergence of SMRs

Microreactors

MWe-scale options

- Heat-pipe cooling
- Remote deployment
- New markets
- Competition with diesel

Advanced Reactors

Beyond large LWRs: non-LWRs, lwSMRs

- Aggressive cost and schedule targets
- Competitiveness via new missions and customers
- Evolving regulatory frameworks

Global commercialization, export, deployment

Development, demonstration, first units

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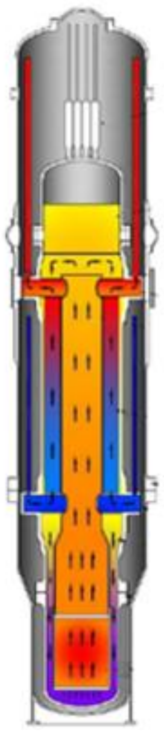
Images of Natrium and Xe-100 copyright of TerraPower and X-Energy respectively.

Advanced Reactor Options on the Menu

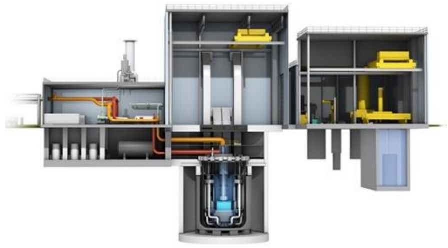
Water-Cooled Reactors



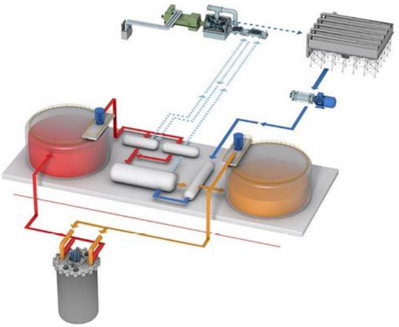
Schematic of the small modular light-water reactor (lwSMR) power module by NuScale

Mature technology with deployment options and wide power range

Sodium Fast Reactor



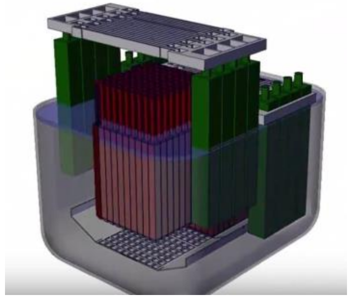
Design rendering of the Natrium reactor, TerraPower's SFR



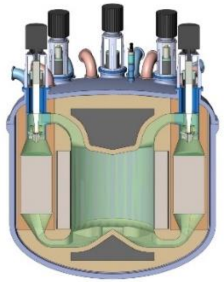
Natrium's integrated molten salt thermal storage loop, enabling 150% power peaking

Highly resource efficient with near-ambient pressure of operation

Molten Salt Reactors



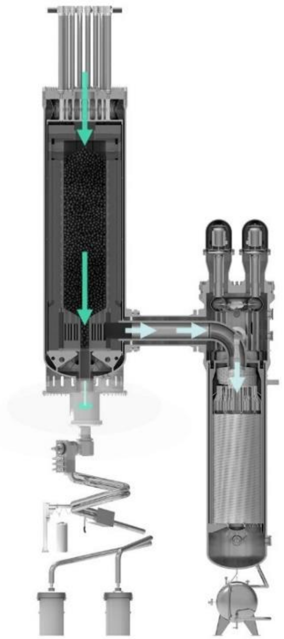
Rendering of Moltex's stable salt reactor, which burns spent LWR fuel.



Rendering of Southern Co. and TerraPower's molten chloride fast reactor.

Wide diversity of coolant and fuel options for various missions

High-Temperature Gas-Cooled Reactor



Rendering of the Xe-100, X-Energy's pebble-bed HTGR.

Test scale experience in Japan for advanced hydrogen production

Microreactors

Design rendering of Westinghouse's eVinci microreactor supplying remote energy

Artist's rendering of Oklo's microreactor power plant

Rapidly deployable, opportunity for industrial heat production

Advanced reactors create flexibility for size, coolant, fuel, products, and more.

Three Fundamental Choices for Nuclear Reactor Design

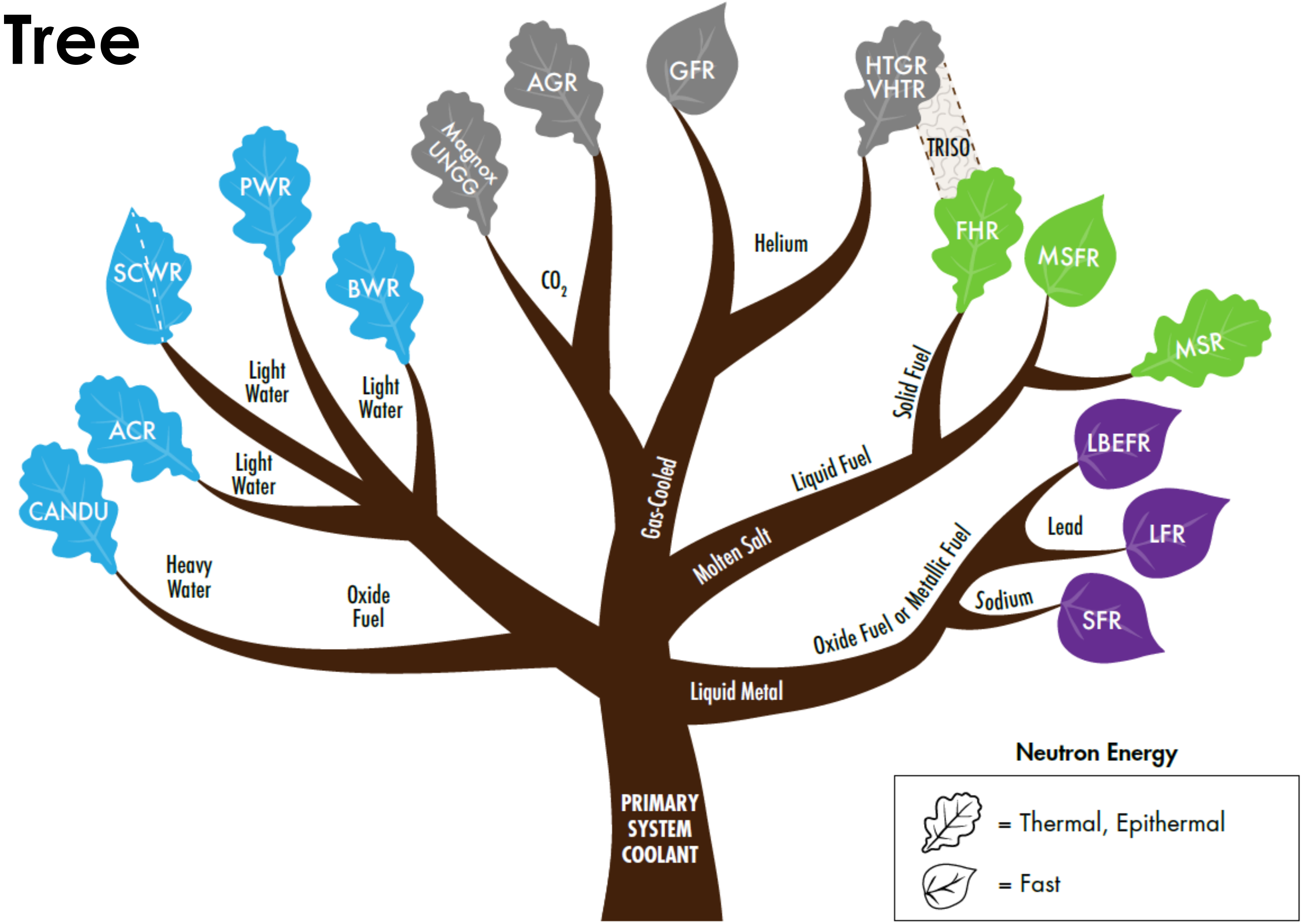
MENU

- Moderator or no moderator (speed/energy of neutrons)
- Fuel and fuel form (fuel cycle)
- **Heat transfer fluid (coolant)**

The Nuclear Family Tree

Common Nuclear Families

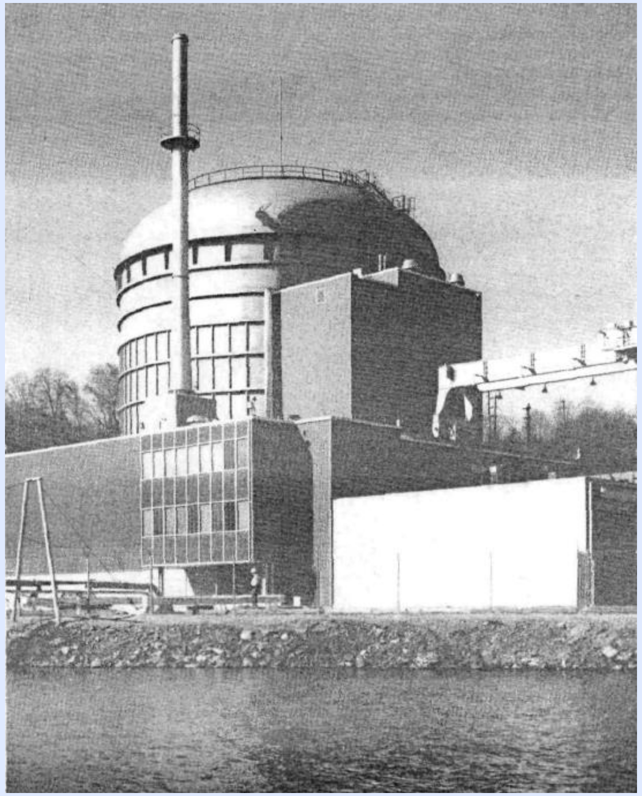
- Gas-cooled Fast Reactor (GFR)
- Lead-cooled Fast Reactor (LFR)
- Sodium Fast Reactor (SFR)
- Supercritical-water-cooled Reactor (SCWR)
- Molten Salt Reactor (MSR)
- High-temperature Gas-cooled Reactor (HTGR)



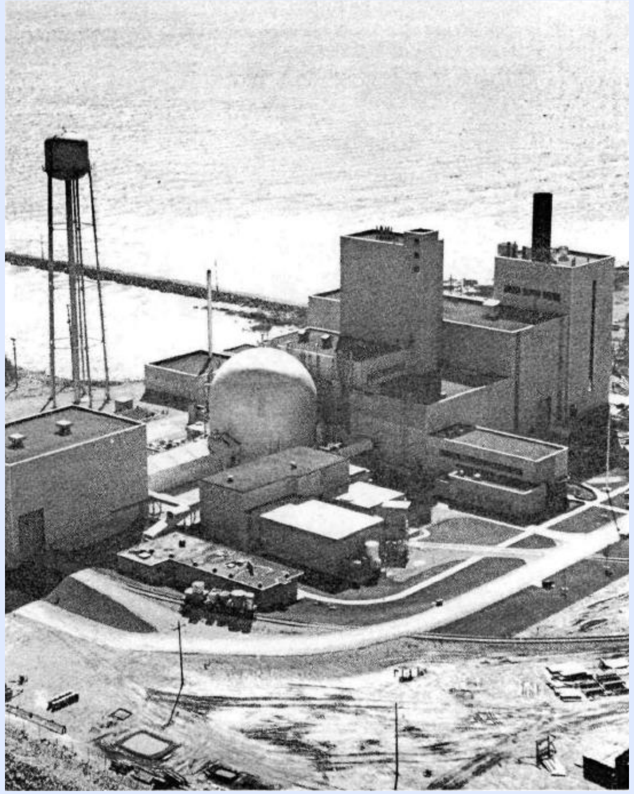
Coolant properties drive many key design attributes and limitations.

Historical Interlude

Advanced (fission) reactors are not necessarily new…



Peach Bottom 1 – High temperature gas-cooled reactor (HTGR)

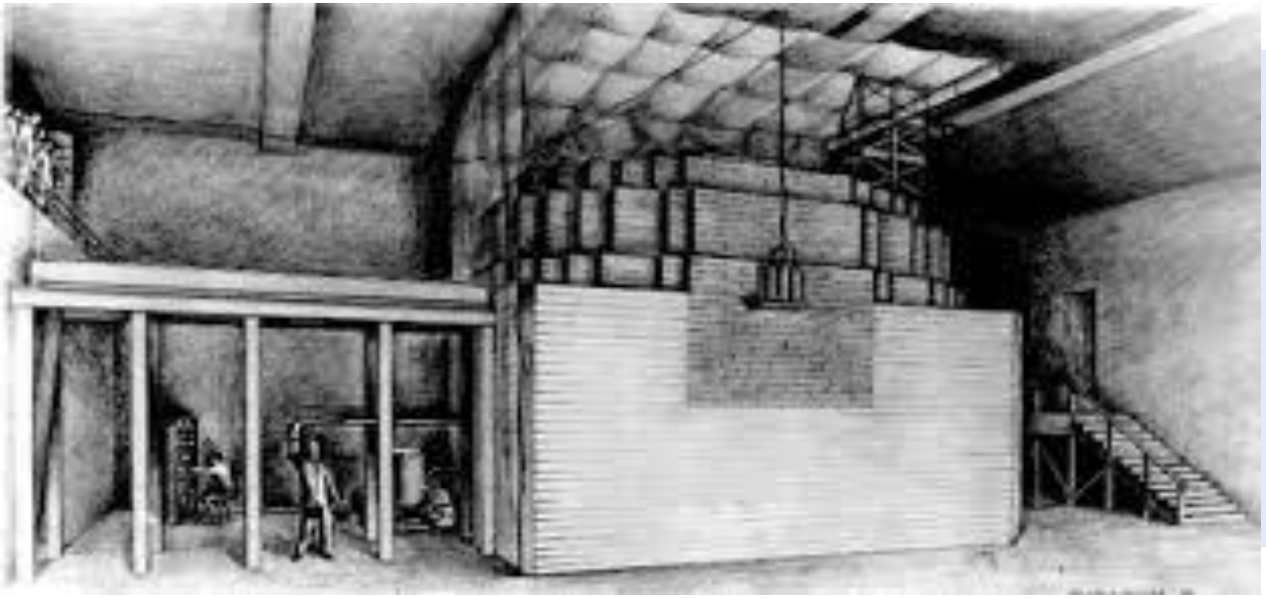


Fermi 1 – Sodium-cooled fast reactor (SFR)

MSRE – Experimental liquid-fueled molten salt reactor (MSR)

Most AR design concepts were demonstrated at some scale in 1950s-60s.

The first nuclear reactors were gas-cooled (air)…

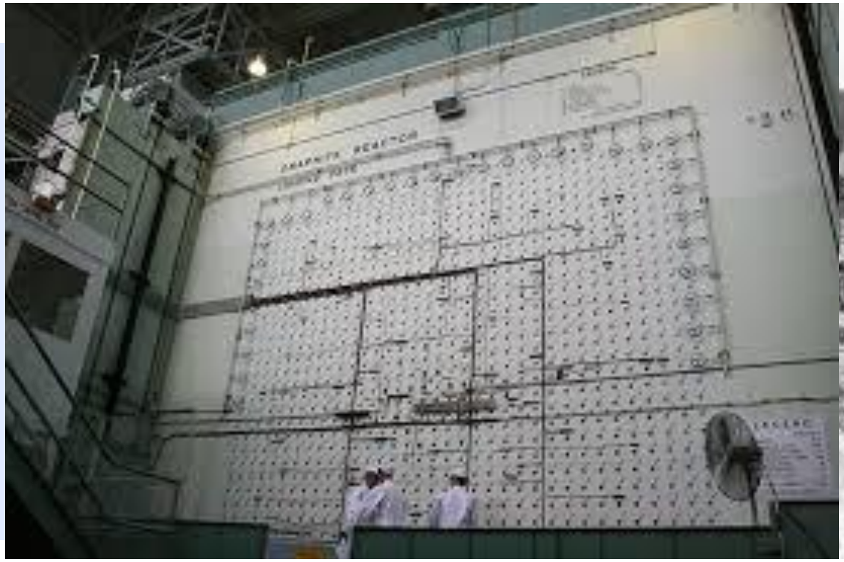


Chicago Pile 1

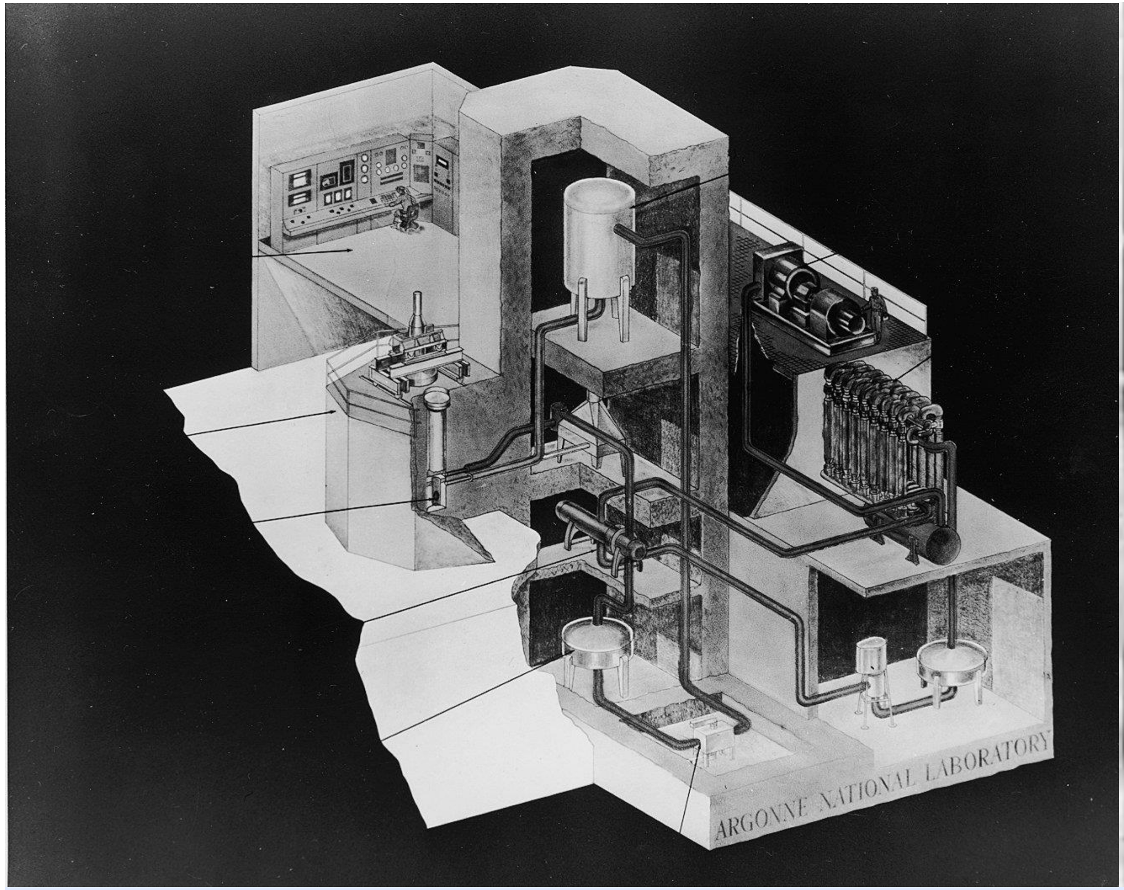
- first reactor to sustain criticality December 1942
- constructed in squash court under University of Chicago Stagg Field football stadium

Oak Ridge X-10 Pile

- became second critical reactor November 1943 and the first designed for continuous operation
- constructed near Clinton Tennessee in rural Bethel Valley (now ORNL)



First nuclear electricity was from a sodium fast reactor…



- **Experimental Breeder Reactor I (EBR-I)**
  - constructed south of Arco, Idaho
  - demonstrated first nuclear electricity generation in December 1953 by powering four light bulbs
  - later powered entire facility

Small Modular Reactors *were* the original nuclear plants…

1954: USS Nautilus (SSN-571)

1962: 1.75 MWe PM-3A NPP
McMurdo Station, Antarctica

Commercial LWR technology originated in naval propulsion programs

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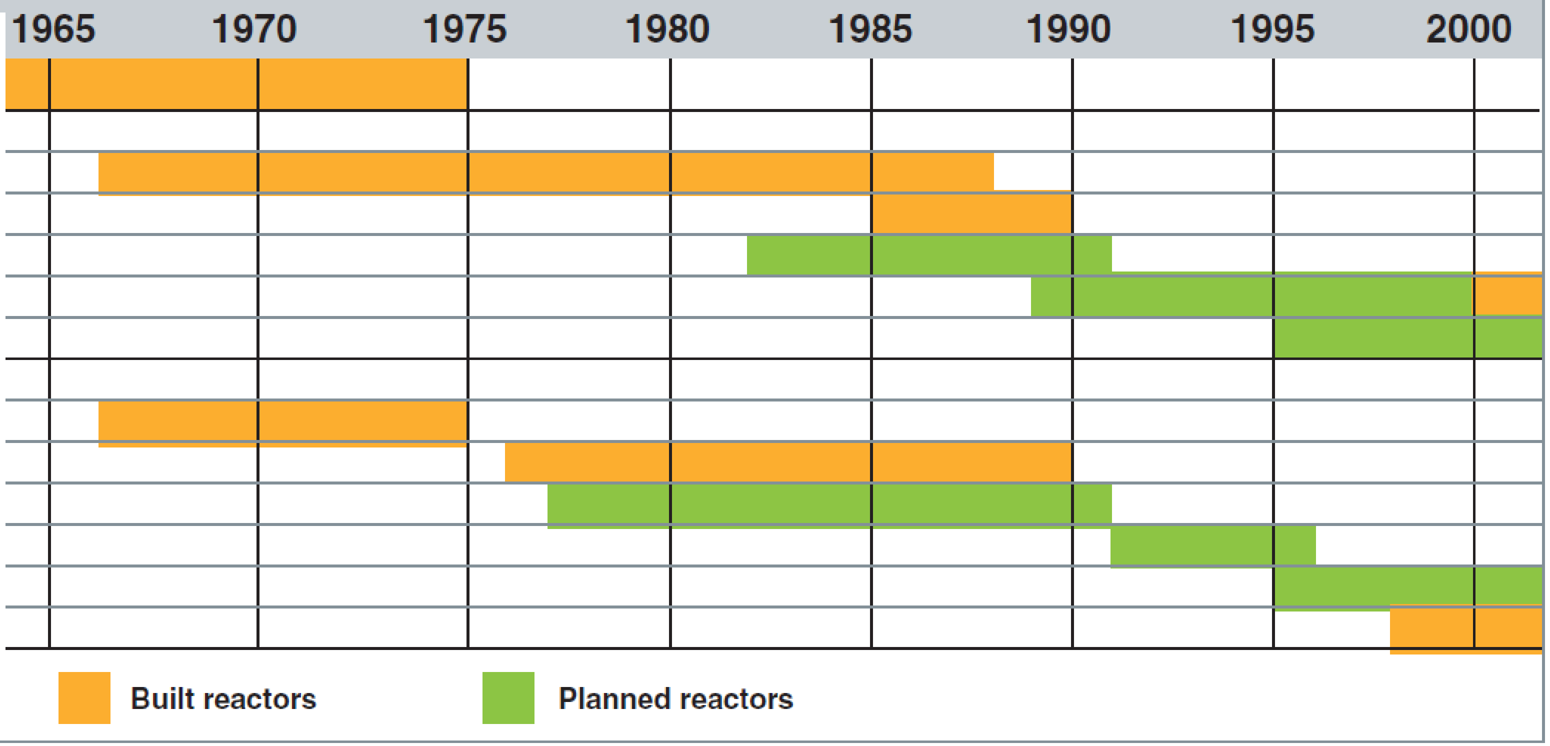
HTGRs have six decades of operating experience…

Country	Name	Power
UK	Dragon	20 MWth
	German family	
Germany	AVR	46 MWth
Germany	THTR	750 MWth
Germany	HTR Modul	200 MWth
China	HTR-10	10 MWth
South-Africa	PBMR	250 MWth
	US family	
USA	Peach Bottom	115 MWth
USA	Fort Saint-Vrain	840 MWth
USA	MHTGR	350 MWth
USA	MHTGR/NPR	
Russia	GT-MHR	600 MWth
Japan	HTTR	30 MWth



Source: CEA, 2006. The recent past and near future of gas-cooled reactors: HTRs.

SFRs also have six decades of operating experience…

Reactor	Country	Full Power to Shutdown	Power (MW_{th})	Power (MW_e)	Design	Fuel	Load Factor
DFR[a]	UK	1962 - 1977	60	15	loop	metal to oxide	21 – 52%[b]
Fermi-1	US	1970 -1972	200	61	loop	metal: U-10%Mo	nd
EBR-II	US	1965 - 1994	62	20	pool	metal: U-Zr	nd
Rapsodie	France	1967 - 1983	24/40	--	loop	oxide	na
BOR-60	Russia	1970 -	55	12	loop	oxide	nd
BN-350	Kazakhstan	1973 - 1999	750	130	loop	oxide	19 – 72%[b]
Phénix	France	1973 - 2010	563	255	pool	oxide	41%
PFR	UK	1974 - 1994	650	250	pool	oxide	27%
KNK-2	Germany	1979 - 1991	58	20	pool	oxide	17%
JOYO	Japan	1979 -	140	--	loop	oxide	na
FFTF	US	1980 - 1992	400	--	loop	oxide	na
BN-600	Russia	1980 -	1470	600	pool	oxide	74%
Super-Phénix	France	1984 - 1998	2990	1242	pool	oxide	8%
FBTR	India	1985 -	40	--	loop	carbide	na
MONJU	Japan	1988 -	714	280	loop	oxide	nd
CEFR	China	2010 -	65	23	pool	oxide	nd
PFBR	India	construction	1253	500	pool	oxide	--
BN-800	Russia	2015 -	2100	870	pool	oxide	nd

[a]DFR coolant was NaK; all others employ(ed) Na metal.

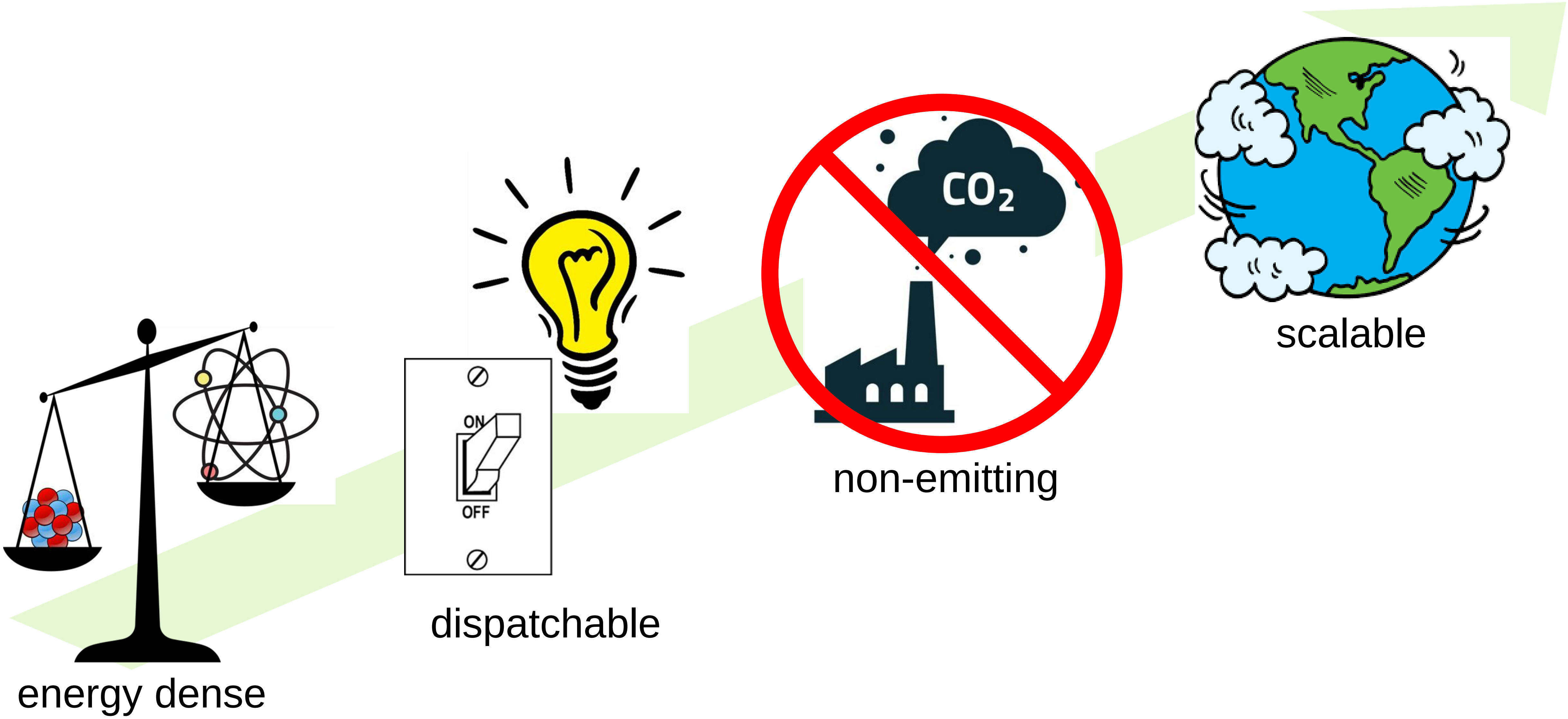
[b]Ranges provided for reactors with insufficient IAEA PRIS data for calculation of cumulative average load factors.

nd = no data; na = not applicable

Source: IAEA PRIS Database; Waltar et al., 2012

Options, Opportunities, and Value

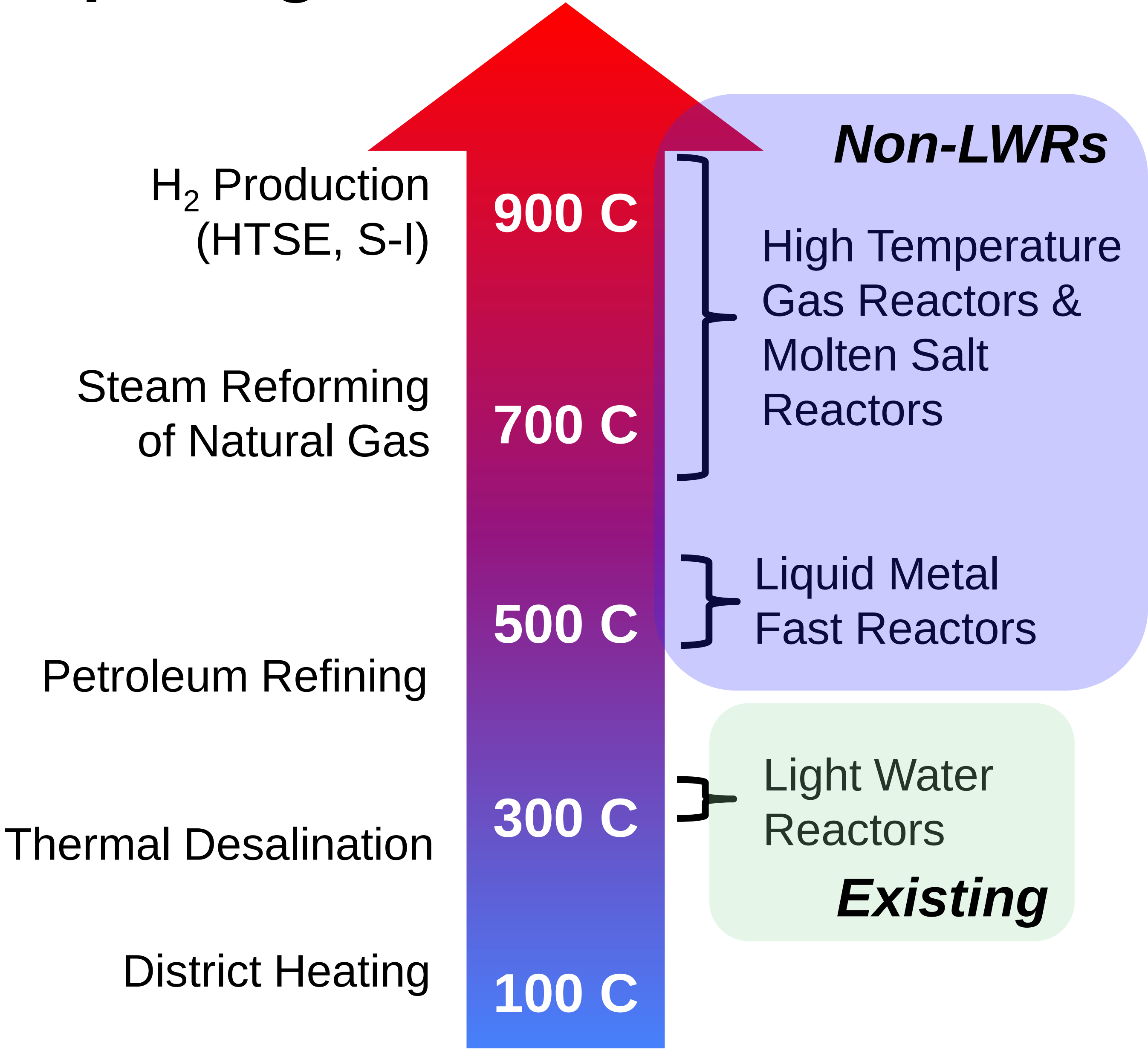
The nuclear bundle…four key attributes in one package!



Expanded options bring compelling benefits.

- Higher temperatures
  - access to new markets with new products
  - higher efficiency electricity production
  - reduced penalty for dry cooling
- Lower pressures
  - lower material and component costs
  - lower consequences of upsets
- Inherent safety and small physical, environmental footprint
  - favorable siting for near industrial end-users and population centers

Nuclear beyond baseload electricity!



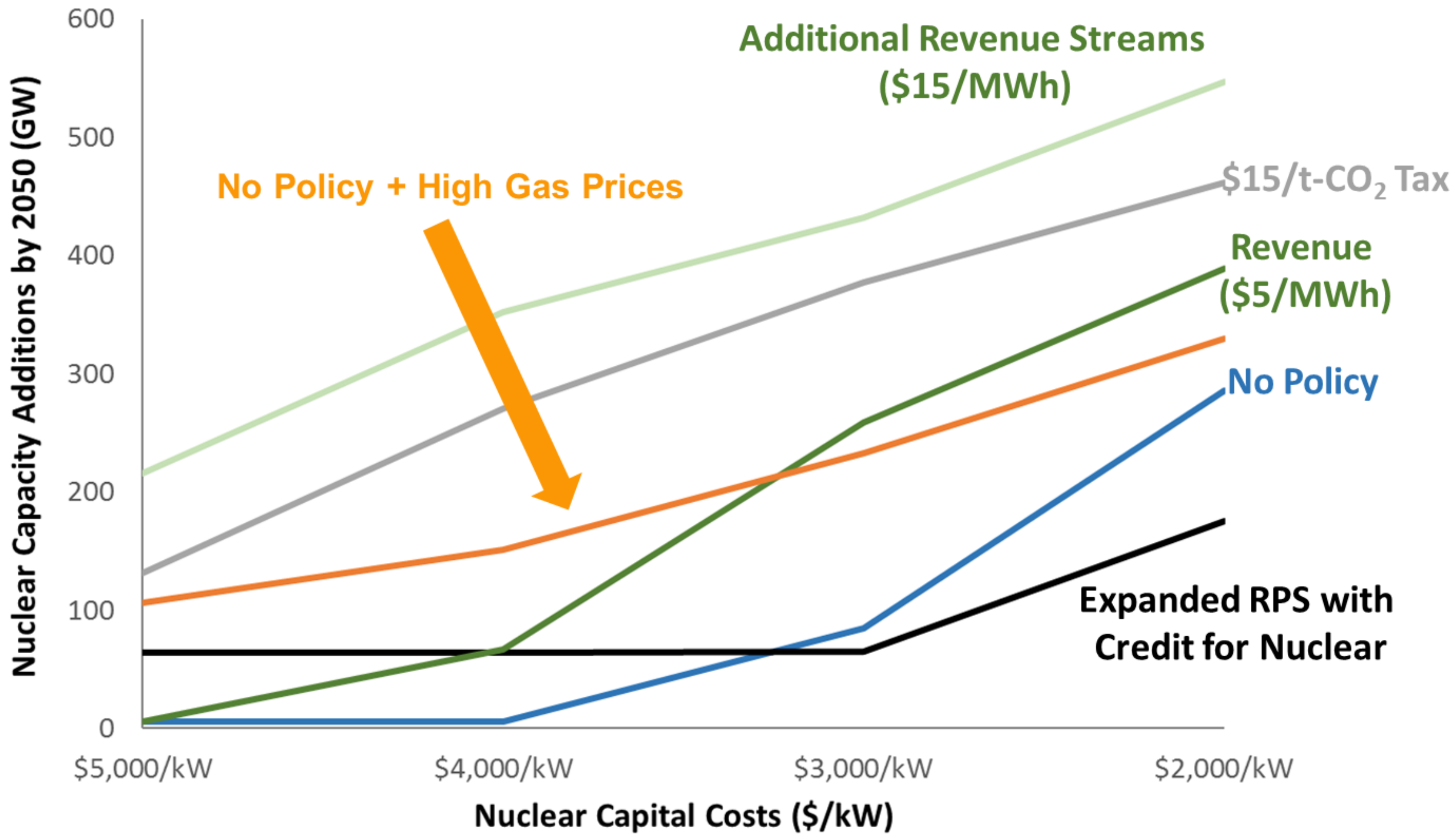
More Options from Greater Flexibility

EPRI (2017) Report No. 3002010479

Attribute	Sub-Attribute	Benefits
Operational Flexibility	Maneuverability	Load following
	Compatibility with Hybrid Energy Systems and Polygeneration	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified Fuel Use	Economics and security of fuel supply
	Island Operation	System resiliency, remote power, micro-grid, emergency power applications
Deployment Flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product Flexibility	Electricity	Reliable, dispatchable power supply
	Process Heat	Reliable, dispatchable process heat supply
	Radioisotopes	Unique or high demand isotopes supply

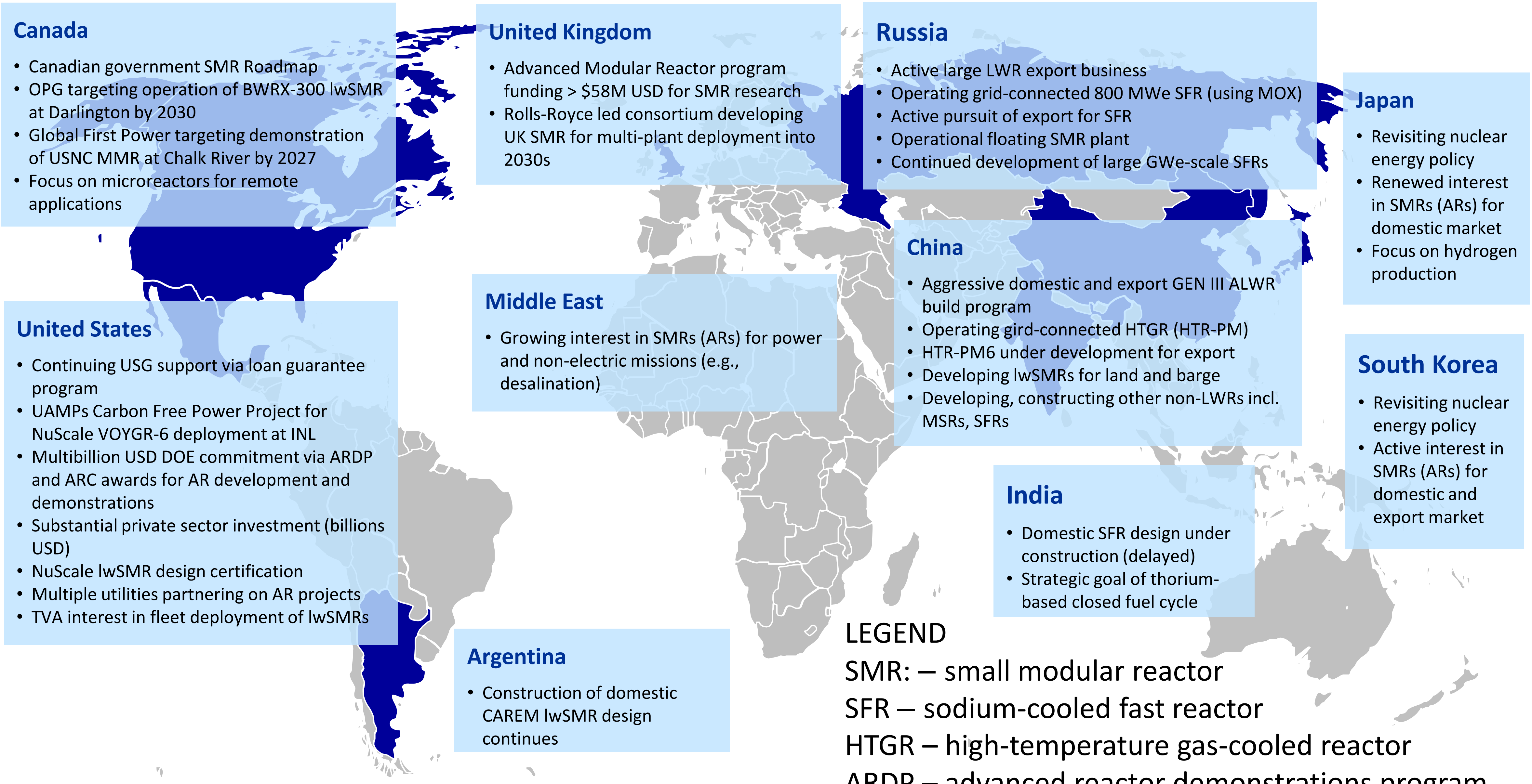
Cost, Policy, and Revenue All Drive Nuclear Competitiveness

Exploring the Role of Advanced Nuclear in Future Energy Markets. March 2018, Report 3002011803



- Non-electricity revenues and policy can drive deployment as much as cost
- Additional revenue streams provide greater investment certainty than other support
- …but competitiveness of nuclear will also be impacted by competing technologies

Advanced nuclear…no longer *if* but *when* and *by whom.*



Canada

- Canadian government SMR Roadmap
- OPG targeting operation of BWRX-300 lwSMR at Darlington by 2030
- Global First Power targeting demonstration of USNC MMR at Chalk River by 2027
- Focus on microreactors for remote applications

United Kingdom

- Advanced Modular Reactor program funding > $58M USD for SMR research
- Rolls-Royce led consortium developing UK SMR for multi-plant deployment into 2030s

Russia

- Active large LWR export business
- Operating grid-connected 800 MWe SFR (using MOX)
- Active pursuit of export for SFR
- Operational floating SMR plant
- Continued development of large GWe-scale SFRs

Japan

- Revisiting nuclear energy policy
- Renewed interest in SMRs (ARs) for domestic market
- Focus on hydrogen production

United States

- Continuing USG support via loan guarantee program
- UAMPs Carbon Free Power Project for NuScale VOYGR-6 deployment at INL
- Multibillion USD DOE commitment via ARDP and ARC awards for AR development and demonstrations
- Substantial private sector investment (billions USD)
- NuScale lwSMR design certification
- Multiple utilities partnering on AR projects
- TVA interest in fleet deployment of lwSMRs

Middle East

- Growing interest in SMRs (ARs) for power and non-electric missions (e.g., desalination)

China

- Aggressive domestic and export GEN III ALWR build program
- Operating gird-connected HTGR (HTR-PM)
- HTR-PM6 under development for export
- Developing lwSMRs for land and barge
- Developing, constructing other non-LWRs incl. MSRs, SFRs

South Korea

- Revisiting nuclear energy policy
- Active interest in SMRs (ARs) for domestic and export market

India

- Domestic SFR design under construction (delayed)
- Strategic goal of thorium-based closed fuel cycle

Argentina

- Construction of domestic CAREM lwSMR design continues

LEGEND
SMR: – small modular reactor
SFR – sodium-cooled fast reactor
HTGR – high-temperature gas-cooled reactor
ARDP – advanced reactor demonstrations program

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