Australian Government

ansto

Latest Developments in Small Modular Reactors

Dr Adi Paterson

Annual Meeting of Four Societies 2015

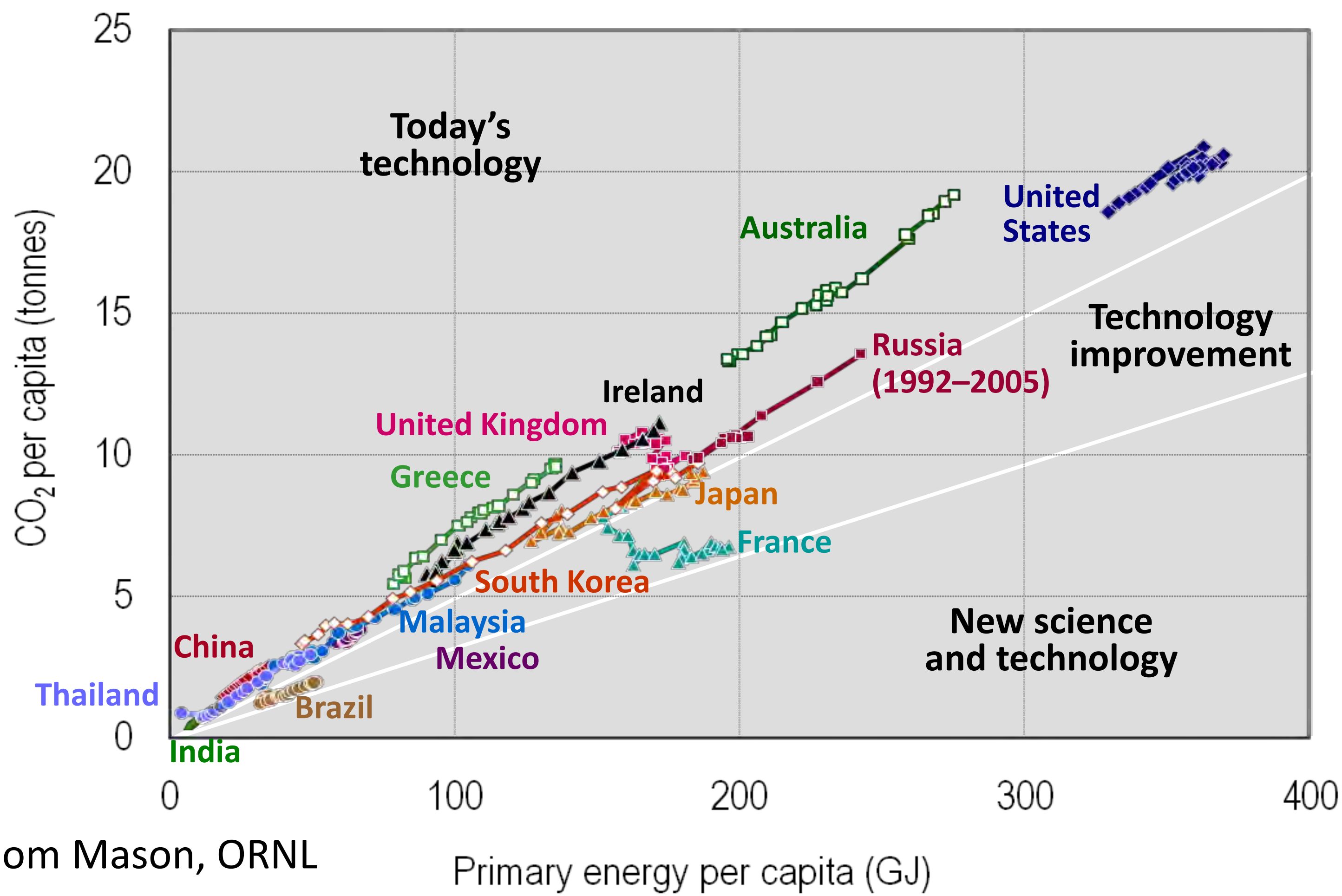
Argonne National Laboratory (West) Idaho, USA

EBR-1 First Nuclear Electricity - December 20 1951

ansto

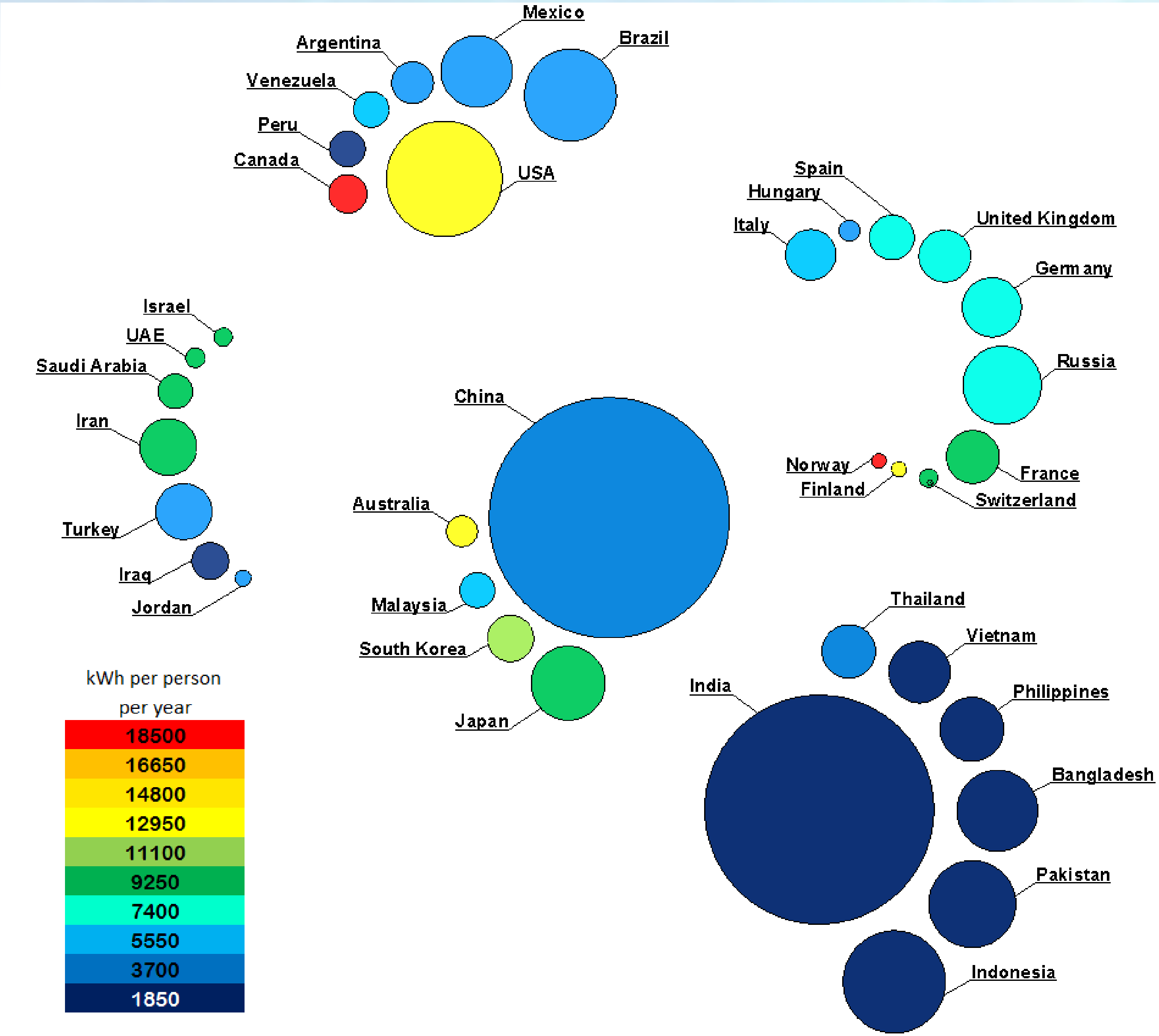
Nuclear-based science benefiting all Australians

Breaking the link
Energy and CO_2 emissions



Source: Thom Mason, ORNL

Electricity use per capita: asymmetrical..



0.67 kWh p.p. per day

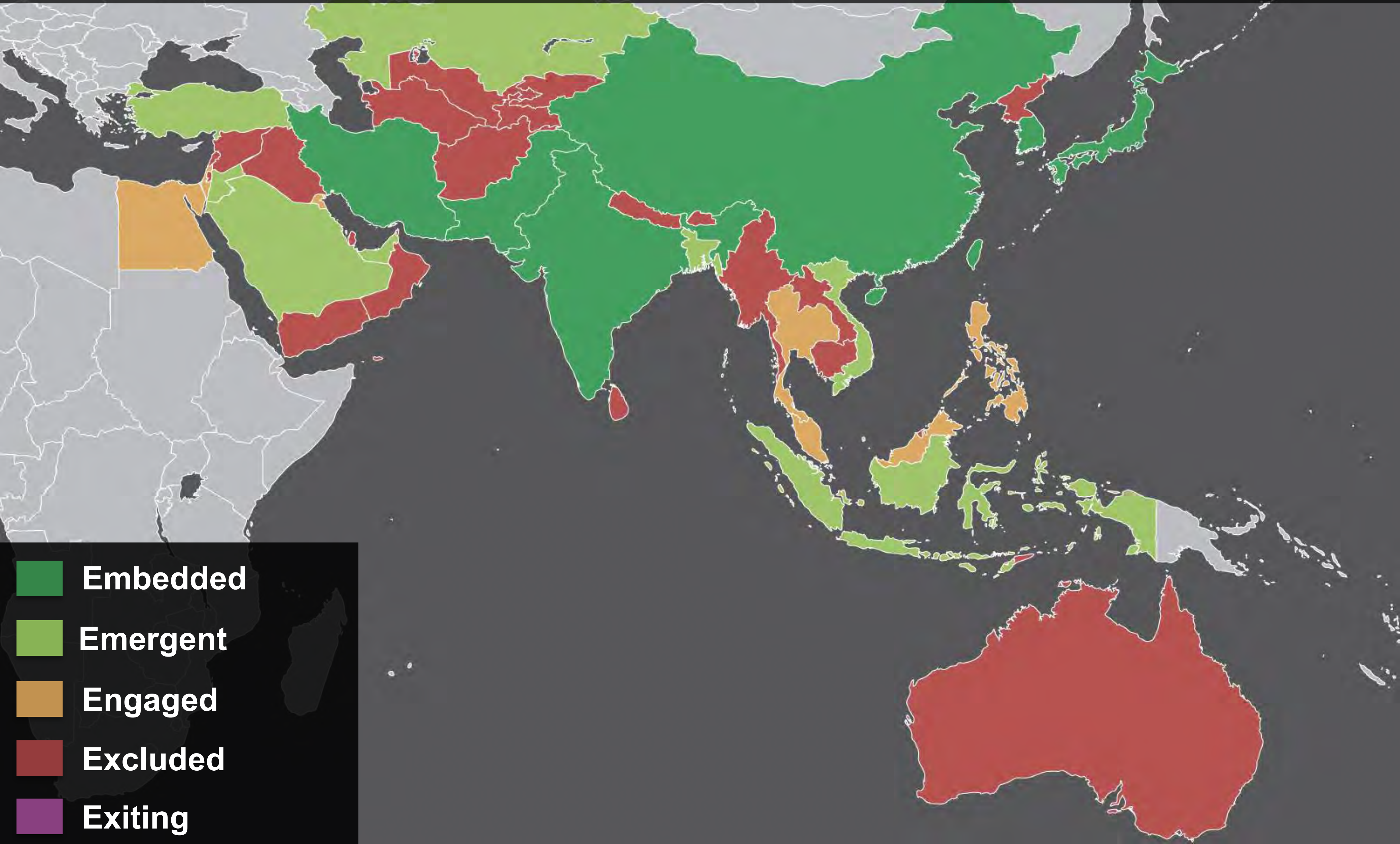
Source: World Bank, 2011
Graphic: Mark Ho

The Nuclear Commitment Scale

J.Powell and K. Naude (ANSTO , 2013)

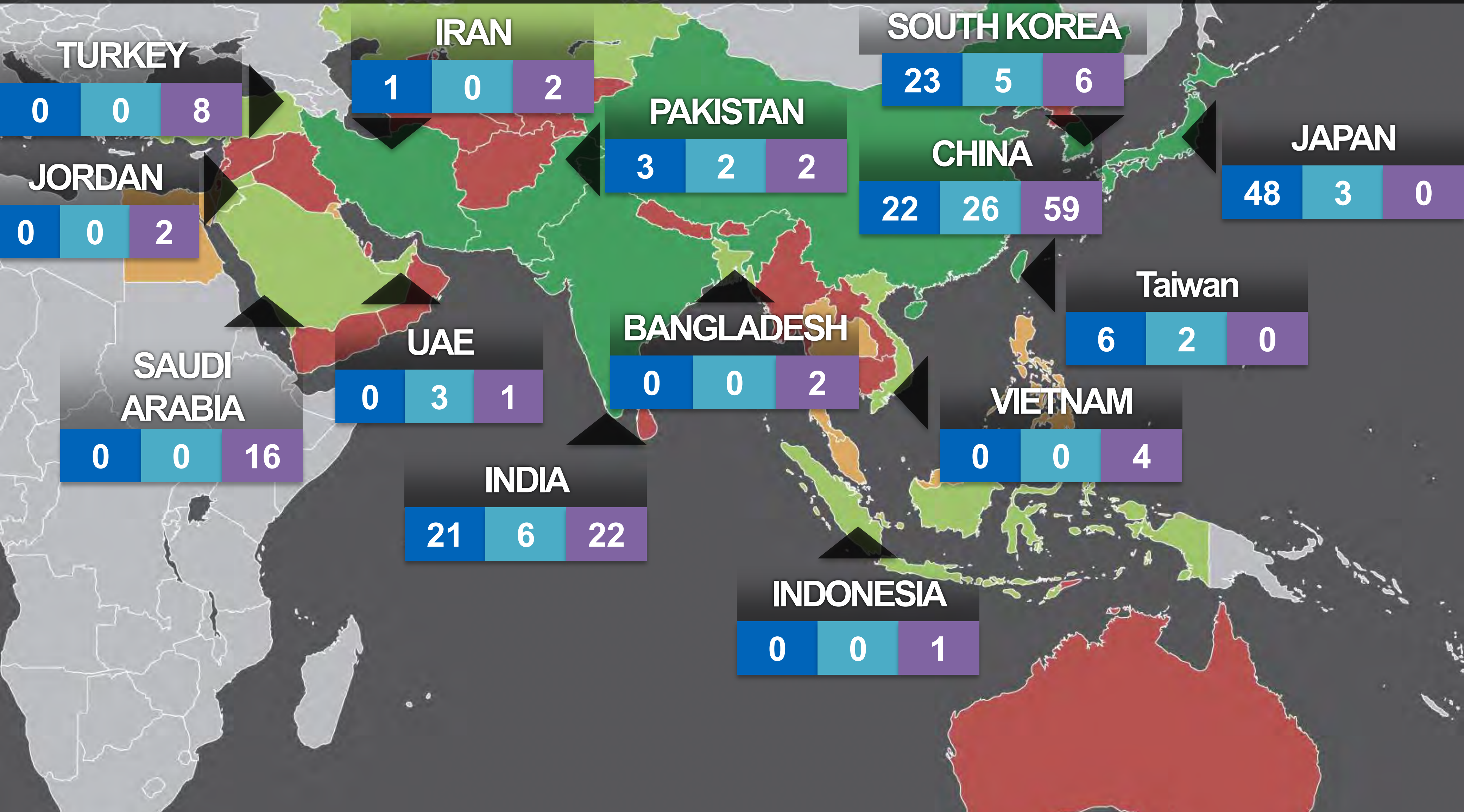
Embedded	Nuclear power: Operational and connected to the grid
Emergent	Nuclear power: plants are planned or under construction
Engaged	Nuclear power: Referenced in official energy policy
Excluded	Nuclear power option excluded from official energy policy
Exiting	Operational nuclear power plants closing Nuclear power is excluded from future energy policy

Nuclear commitment in Asia



Reactors planned, under construction and operational

November 2014



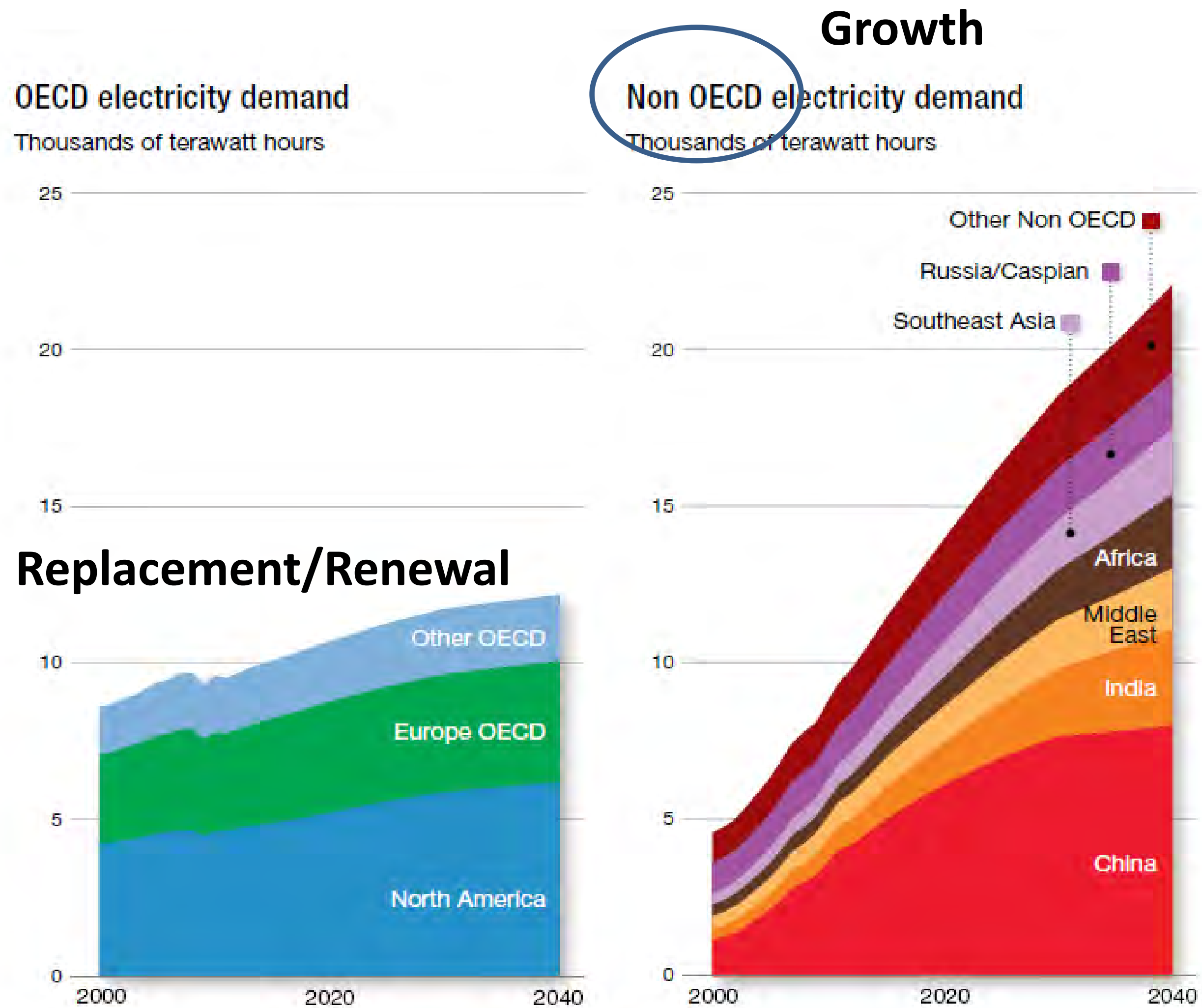
Operational Under construction Planned

Source: WNA

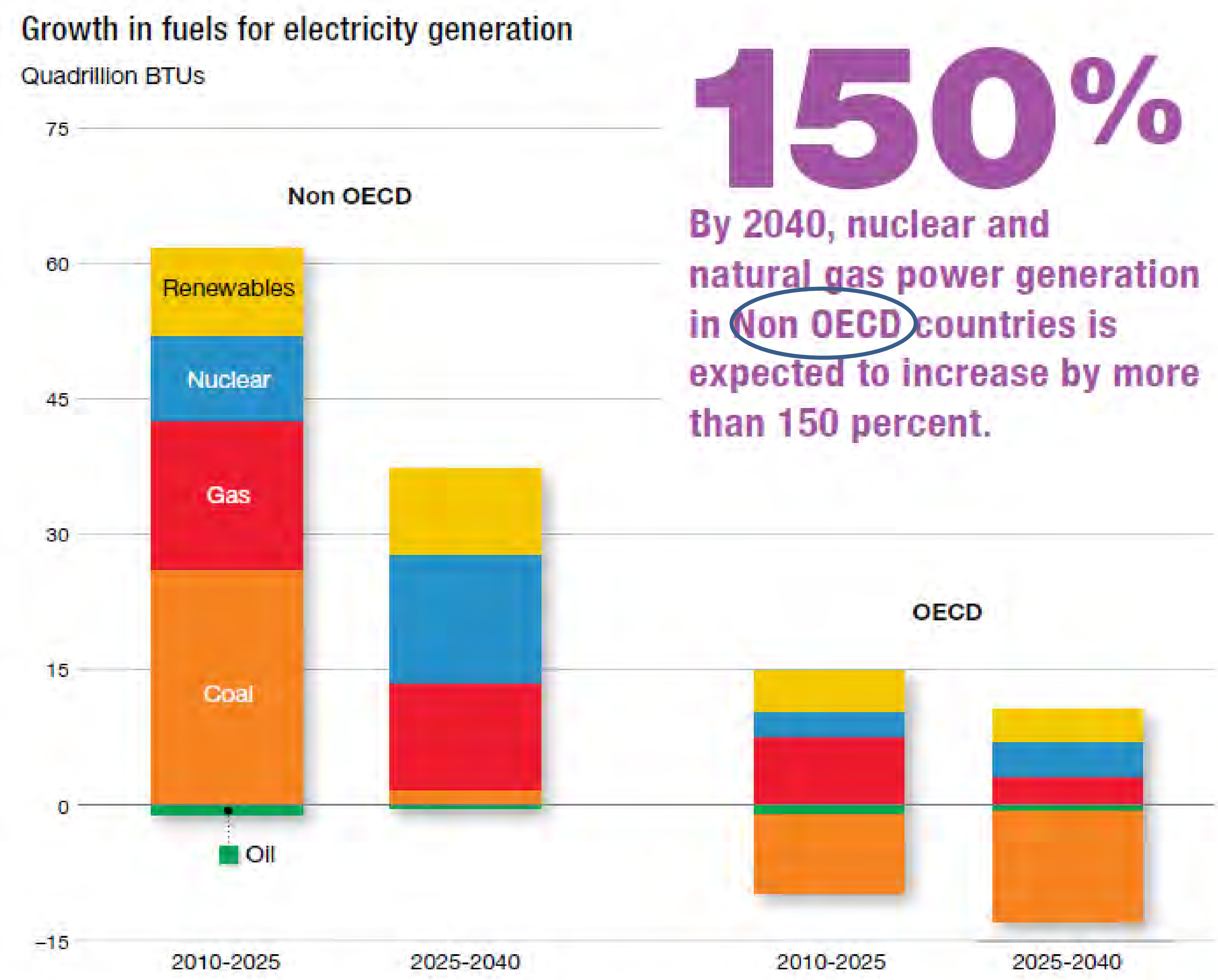
Asymmetrical growth: Global Electricity Demand: 2000 -2040

16,000 terawatts

By 2040, global electricity demand will grow by about 16,000 terawatt hours (about four times the current usage of the U.S.). This growth is driven primarily by an increase in the industrial sector of more than 75 percent, followed by residential/ commercial.



Source: Exxon Mobil Energy Scenarios 2013



Source: Exxon Mobil Energy Scenarios 2013

Generating capacity

Australia
Total 2013
59 GWe

China
Nuclear 2020
58 GWe

Generating capacity

Australia
Total 2013
59 GWe

China
Total 2013
1146 GWe

Generations of Nuclear Energy

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure

1950 1960 1970 1980 1990 2000 2010 2020 2030

Gen I	Gen II	Gen III	Gen III+	Gen IV

Generations of Nuclear Energy

Older Reactors (no more builds)

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

New Reactors (current builds)

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

Evolutionary Designs

Advanced reactors

Generation IV

Revolutionary Designs

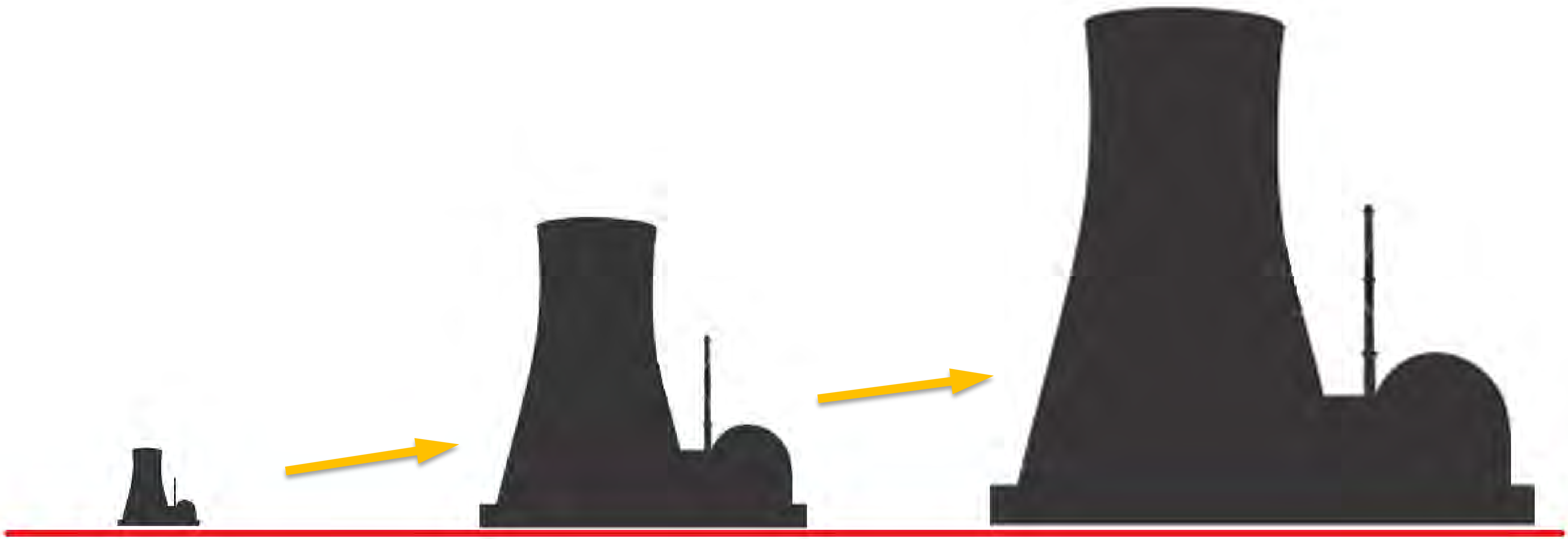
Small Modular Reactors

Gen III+	Gen IV
Integral-PWRs	HTGRs MSRs SFRs LBFRs

1950 1960 1970 1980 1990 2000 2010 2020 2030

Gen I | Gen II | Gen III | Gen III+ | Gen IV

Over the years, reactors have only gotten larger



Shippingport
60 MWe
1958
(PWR test reactor)

Peach Bottom Unit 2
1,180 MWe
1974

Taishan
1,750 MWe
2015

What is an SMR?

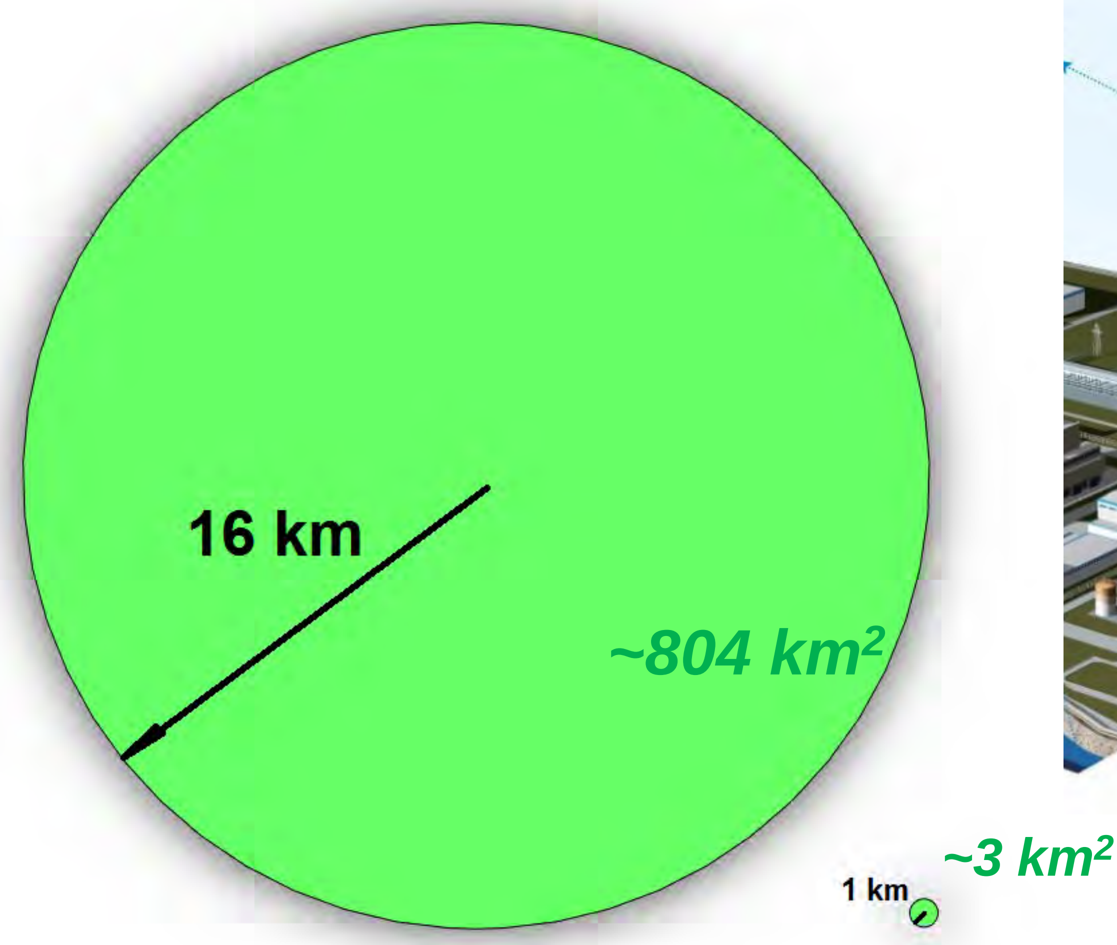
IAEA

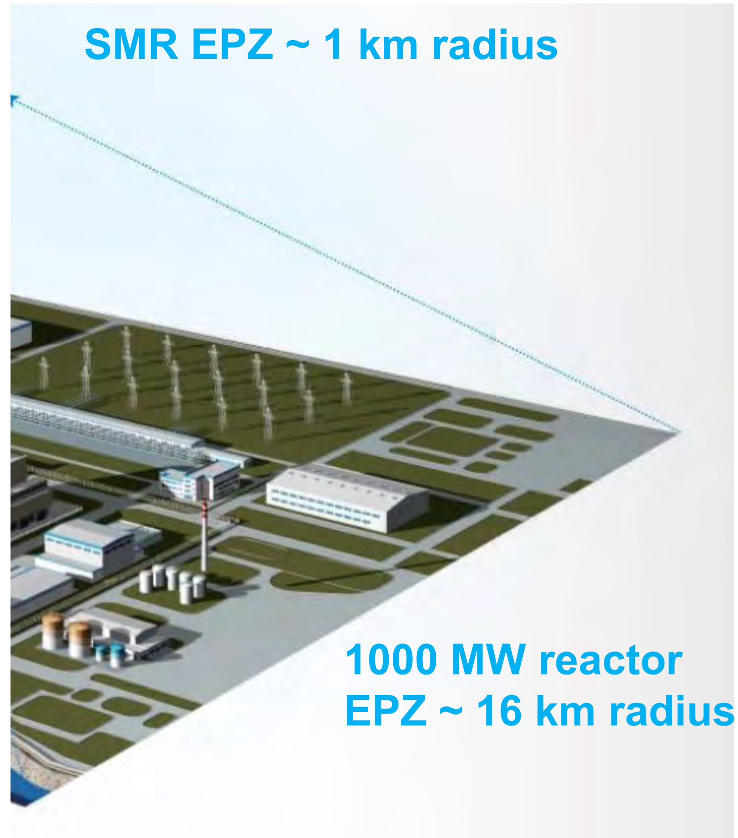
- **S**mall and **M**edium **R**eactors
- Output <700MWe
- Modular
- Share "Balance of Plant"

The Market

- **S**mall **M**odular **R**eactors
- Output <300MWe
- Factory fabricated
- Transportable : rail or road
- Grouped to form larger plants

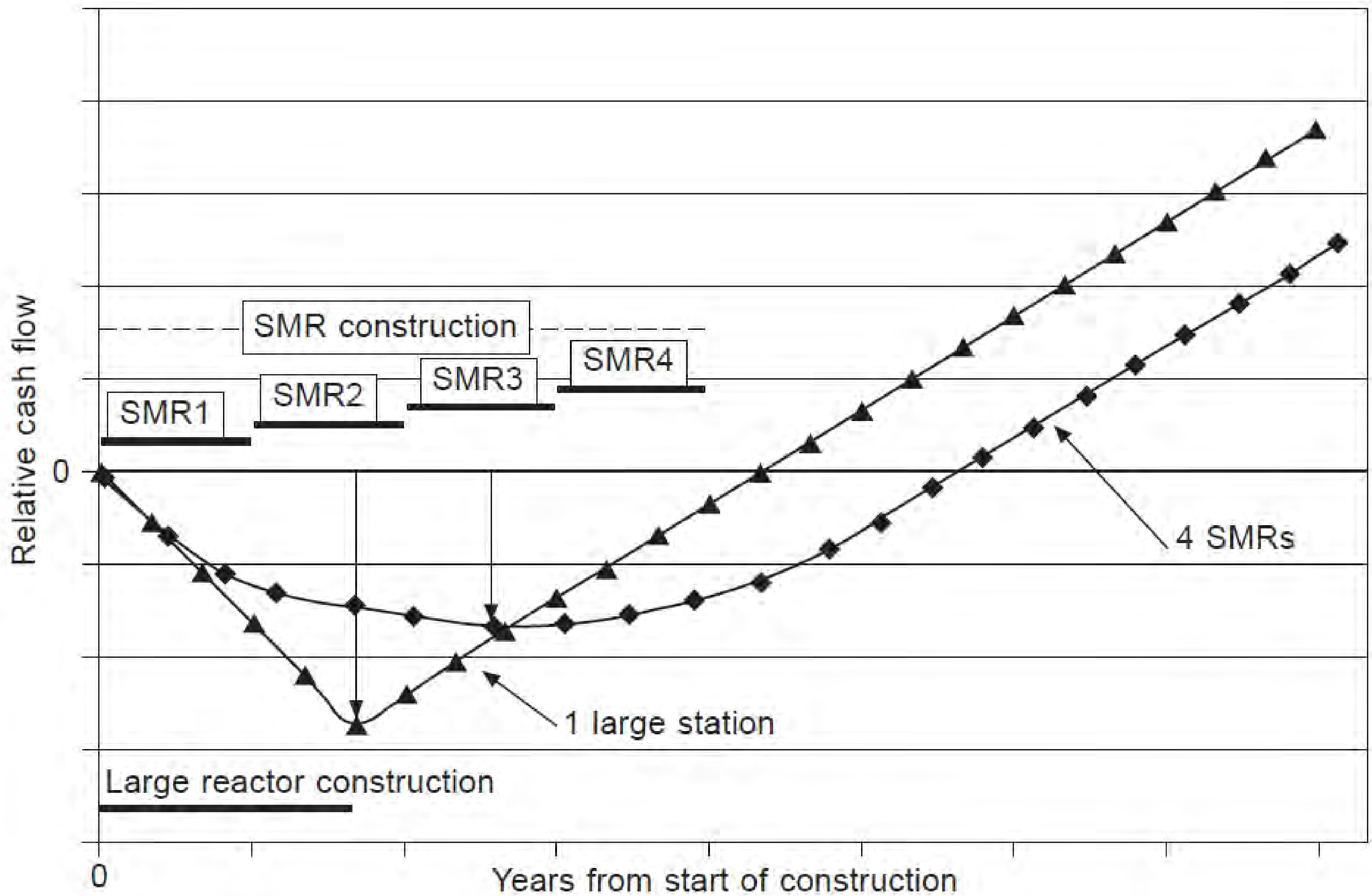
Very small emergency planning zones





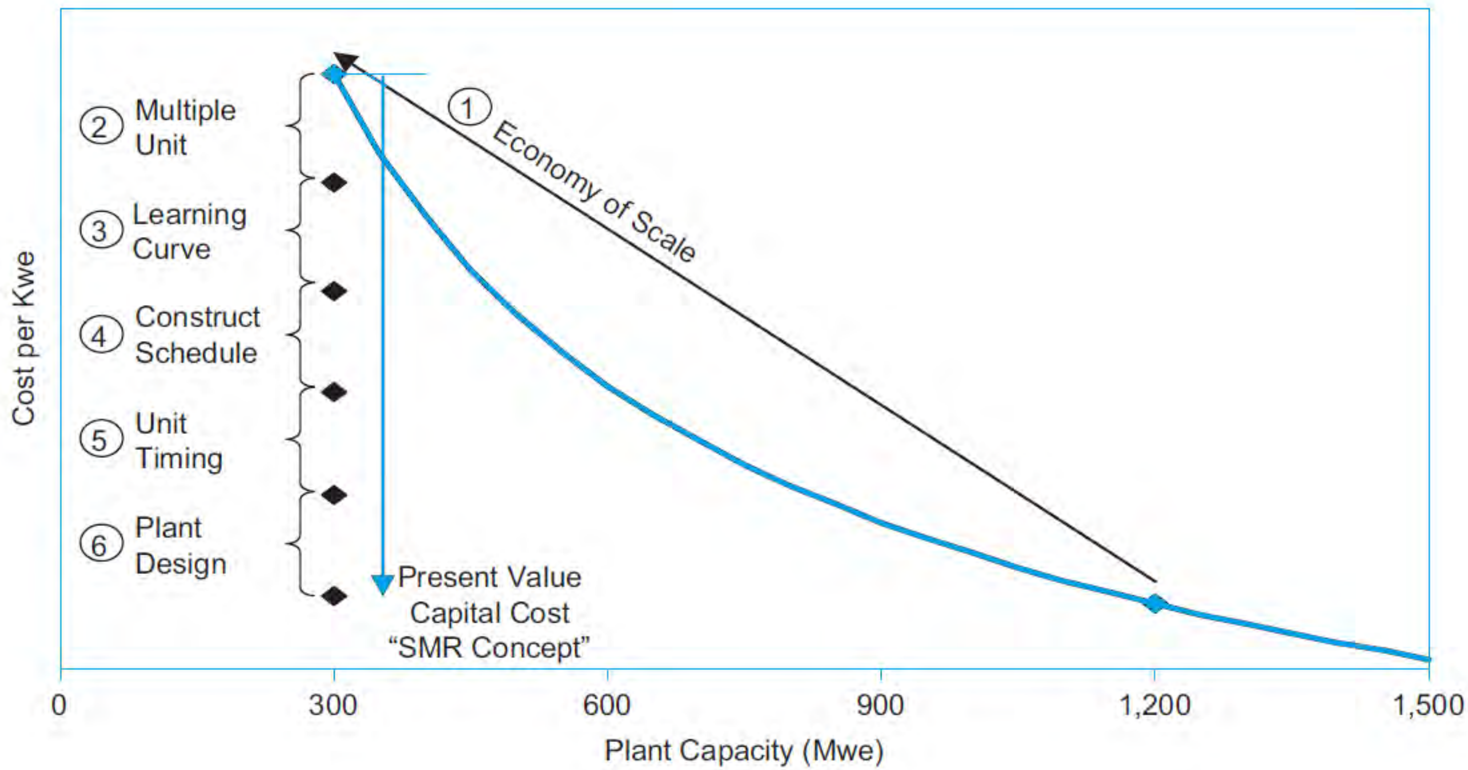
Graphics: CNNC ACP100

Economics



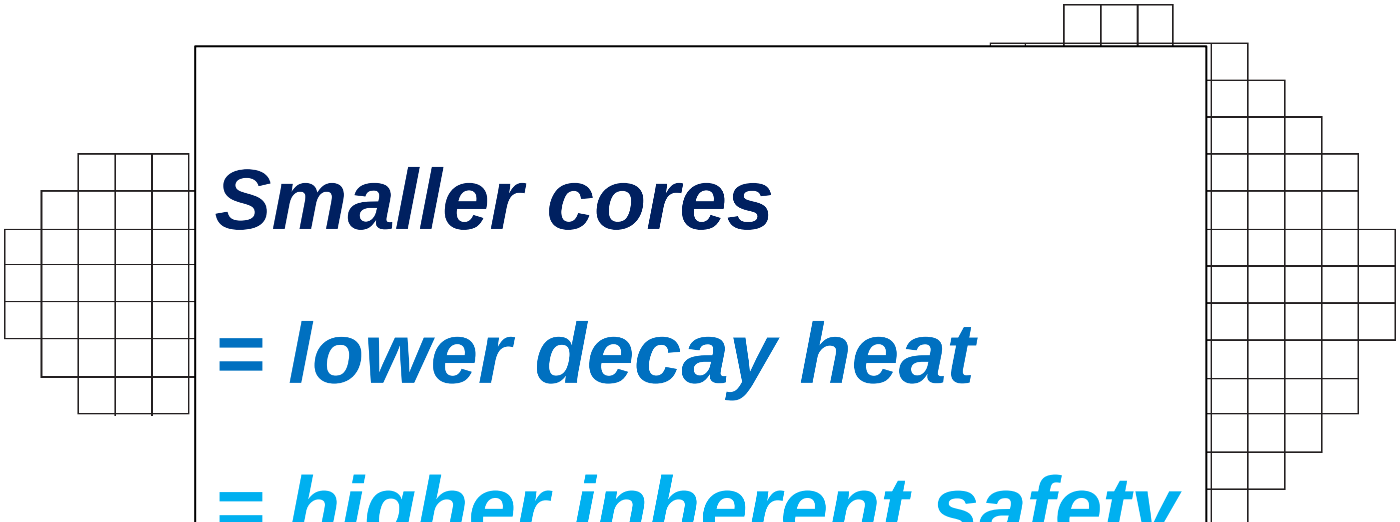
Source: Carelli (2015)

Factors affecting SMRs' LCOE



Source: Mycoff et al.(2011)

Smaller core size



Smaller cores

= lower decay heat

= higher inherent safety

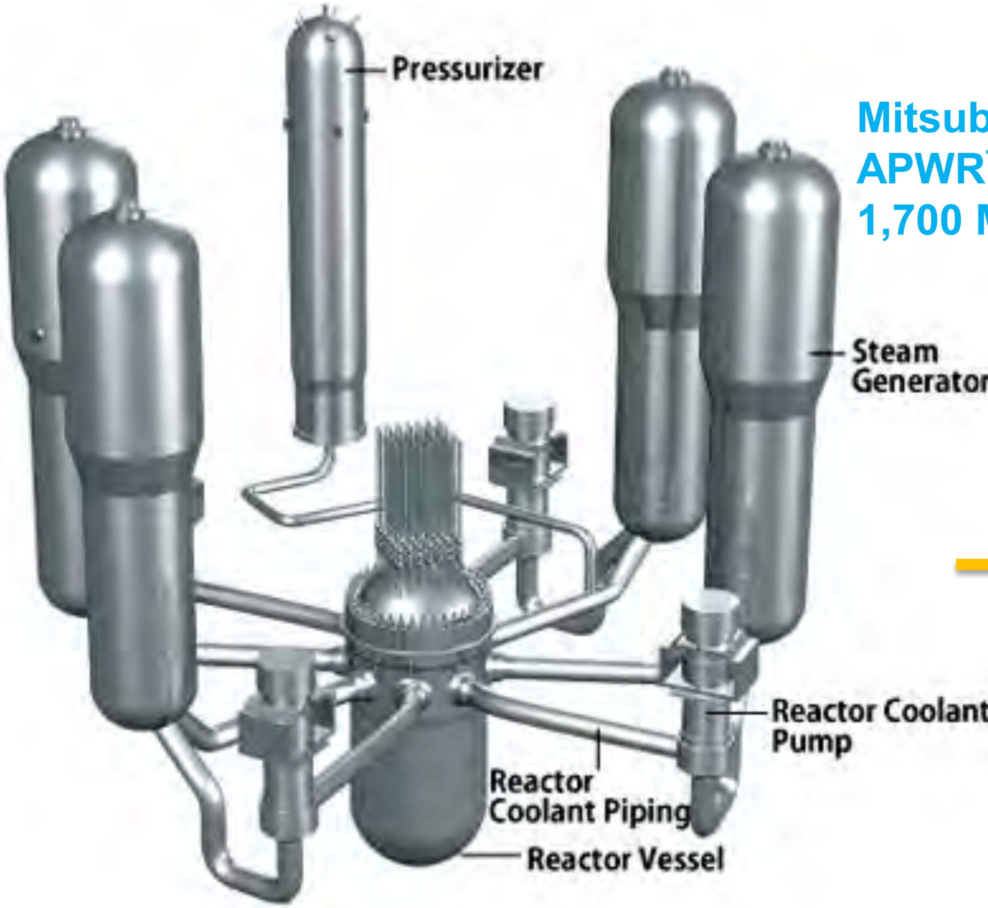
NuScale = 50 MWe

Westinghouse SMR = 225 MWe

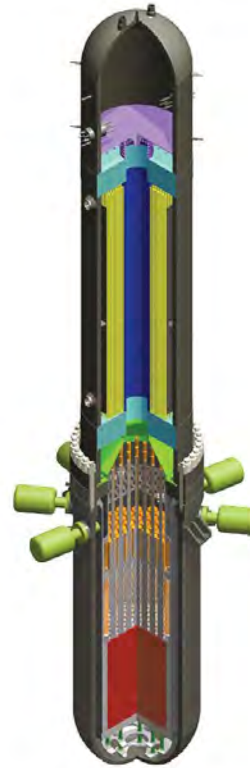
Westinghouse AP-1000 = 1,100 MWe

Source: Worrall (2015)

SMRs: miniaturise & mass produce



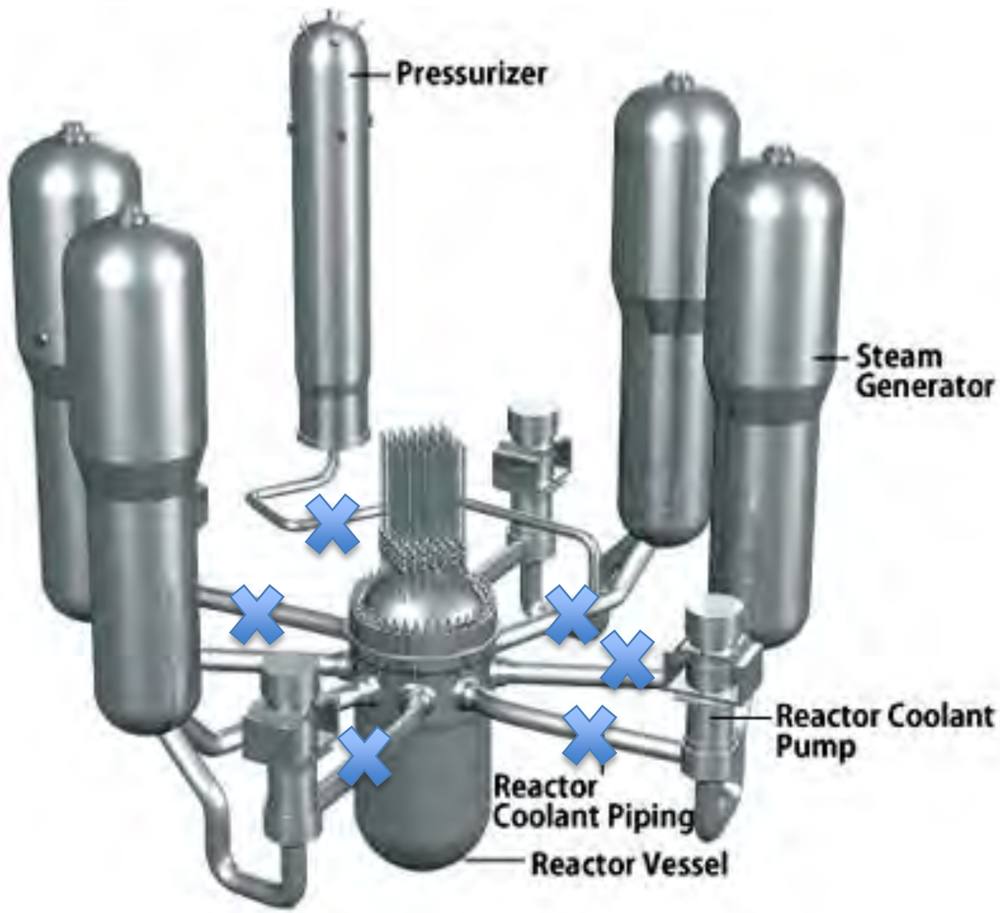
Mitsubishi
APWR™
1,700 MW

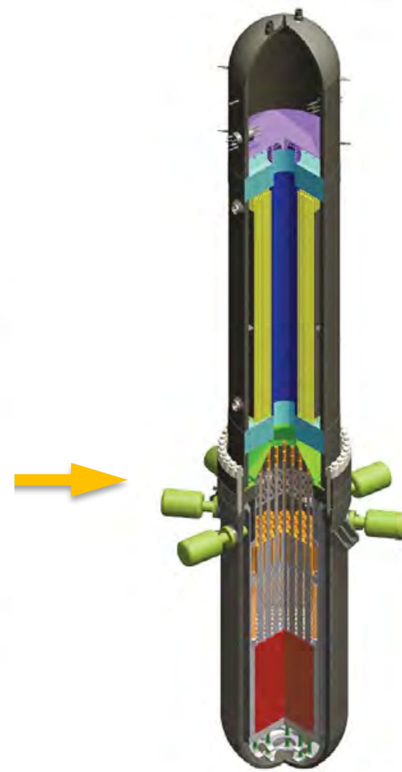


Westinghouse™
SMR
225 MW

Graphics:
Mitsubishi Heavy Industries &
Westinghouse SMR

SMRs
Eliminating large-pipe-break accidents





Westinghouse™ SMR

Graphics:
Mitsubishi Heavy Industries &
Westinghouse SMR

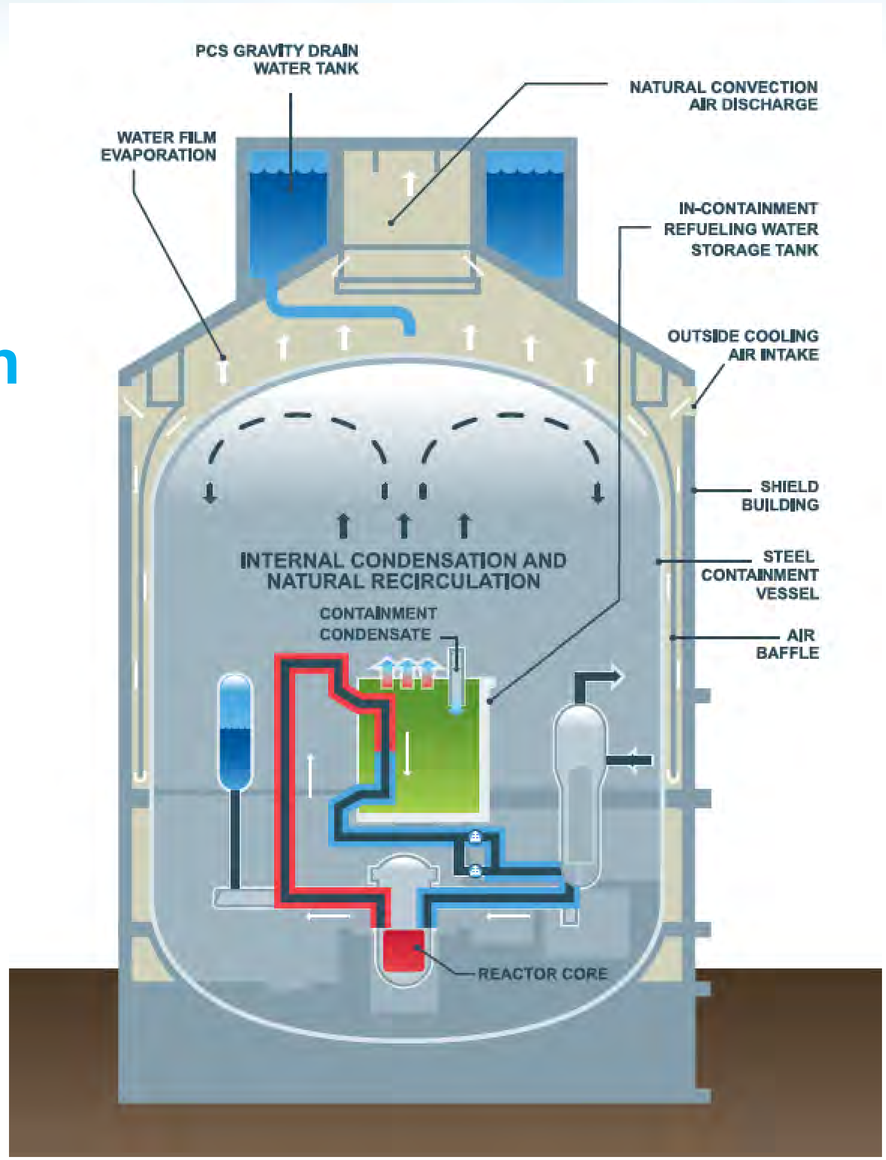
Passive decay heat removal

Passive Elements

Gravity

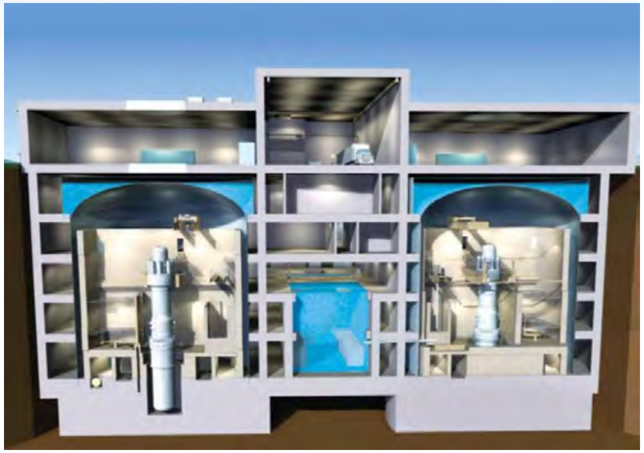
Natural Circulation

Condensation

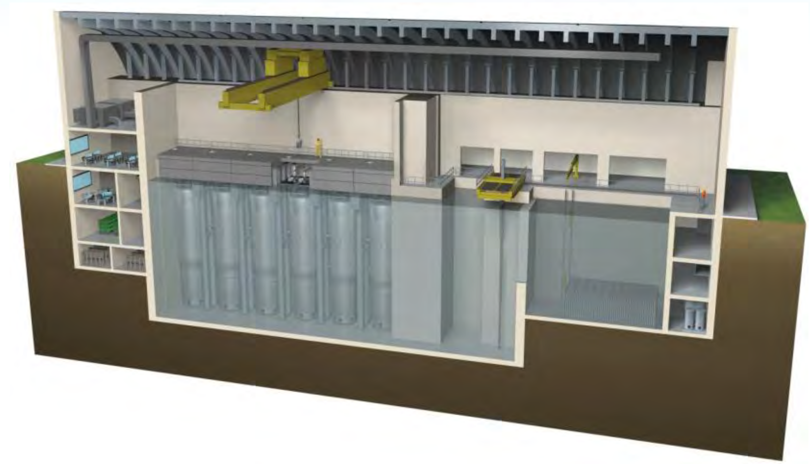


Westinghouse AP-1000™

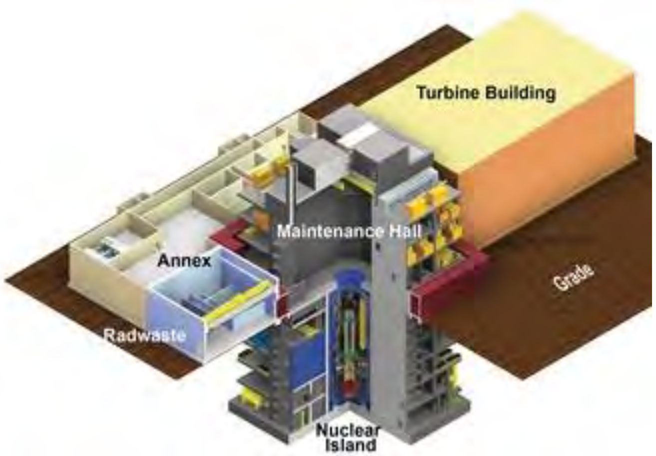
Water reservoirs in SMRs



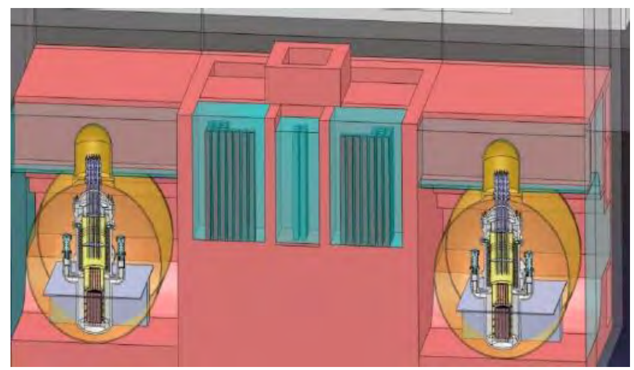
mPower



NuScale



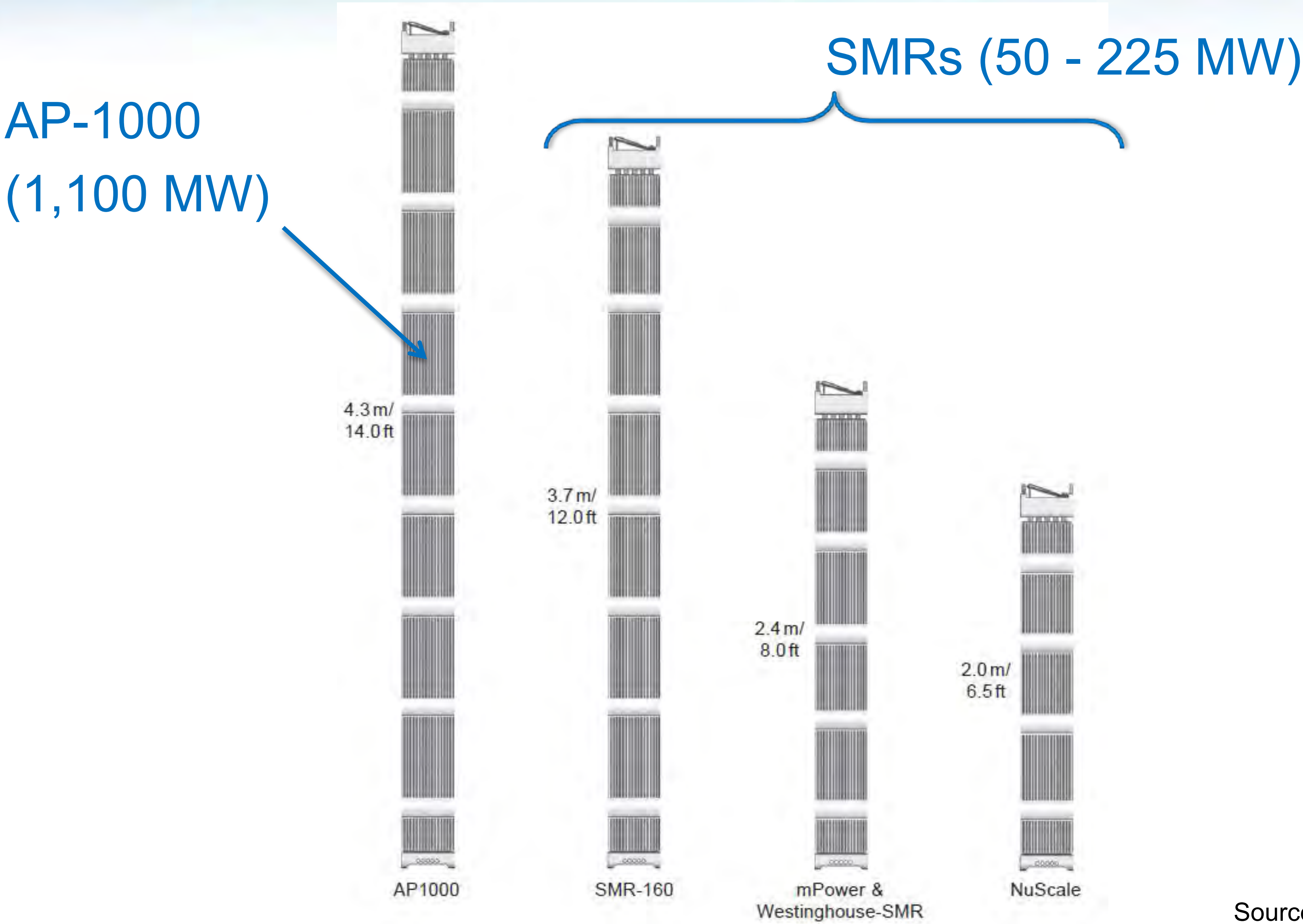
Westinghouse SMR



ACP-100

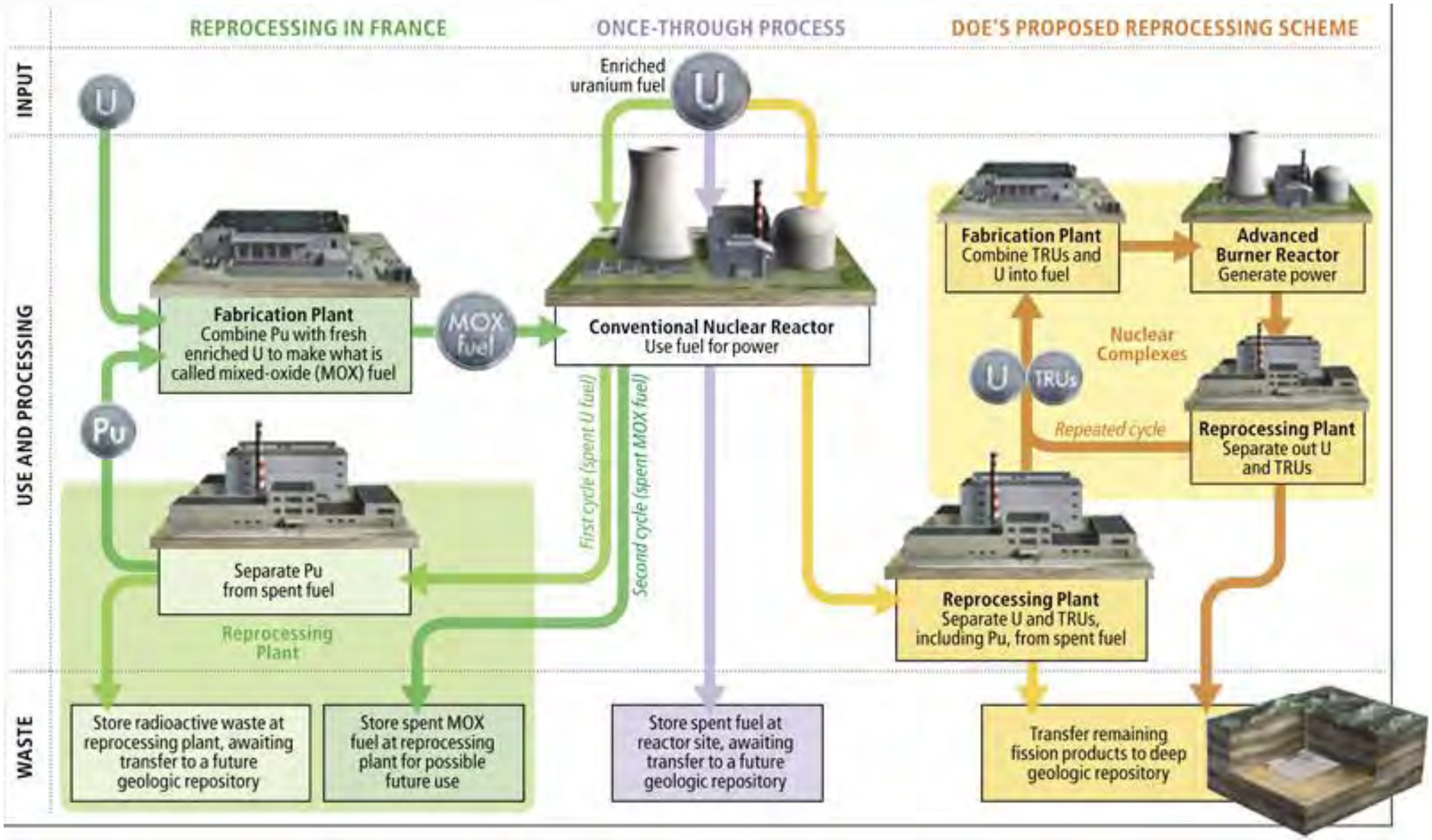
Sources: CNNC, mPower, NuScale

Smaller fuel loading



Source: Worrall (2015)

Fuel cycle

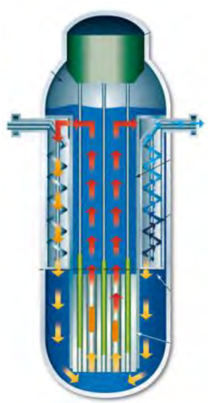


Cassette core swap out = no fuel shuffling

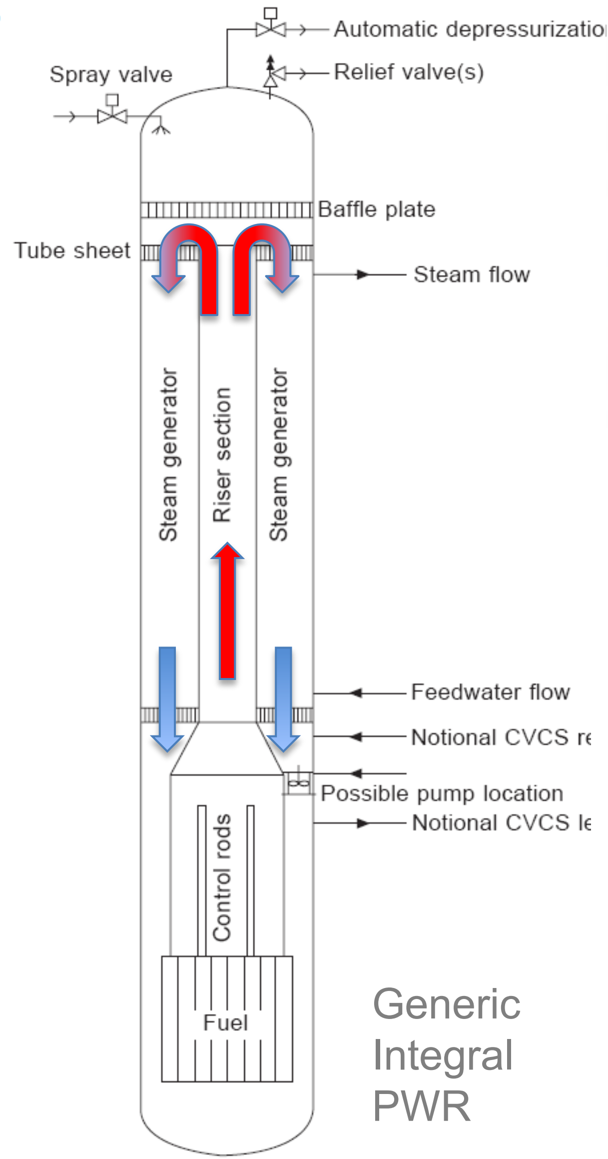
SMRs - iPWRs

Natural Convection
(no pumps, limit ~70 MW)

NuScale
50 MW

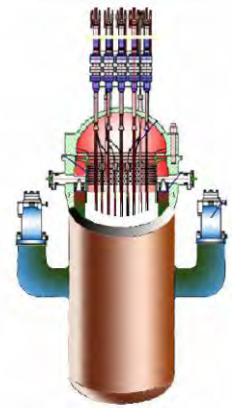


CAREM
33 MW



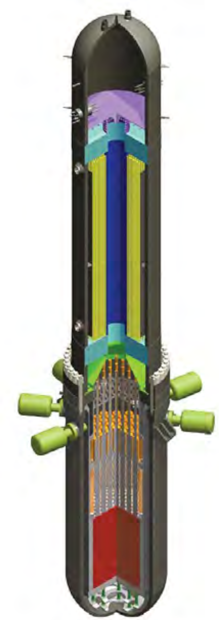
Generic
Integral
PWR

Forced Convection
(pumps)



ACP-100
100 MW

mPower
180 MW



Westinghouse
225 MW

Source: Belles (2015)

i-PWRs under development

SMRs make nuclear more attractive

- Safer
- Smaller, < 300 Mwe
- Emergency planning zone
- Co-generation
- Capital model
- Remote deployment
- Fuel: Buy-burn-return
- Shared approach to licensing

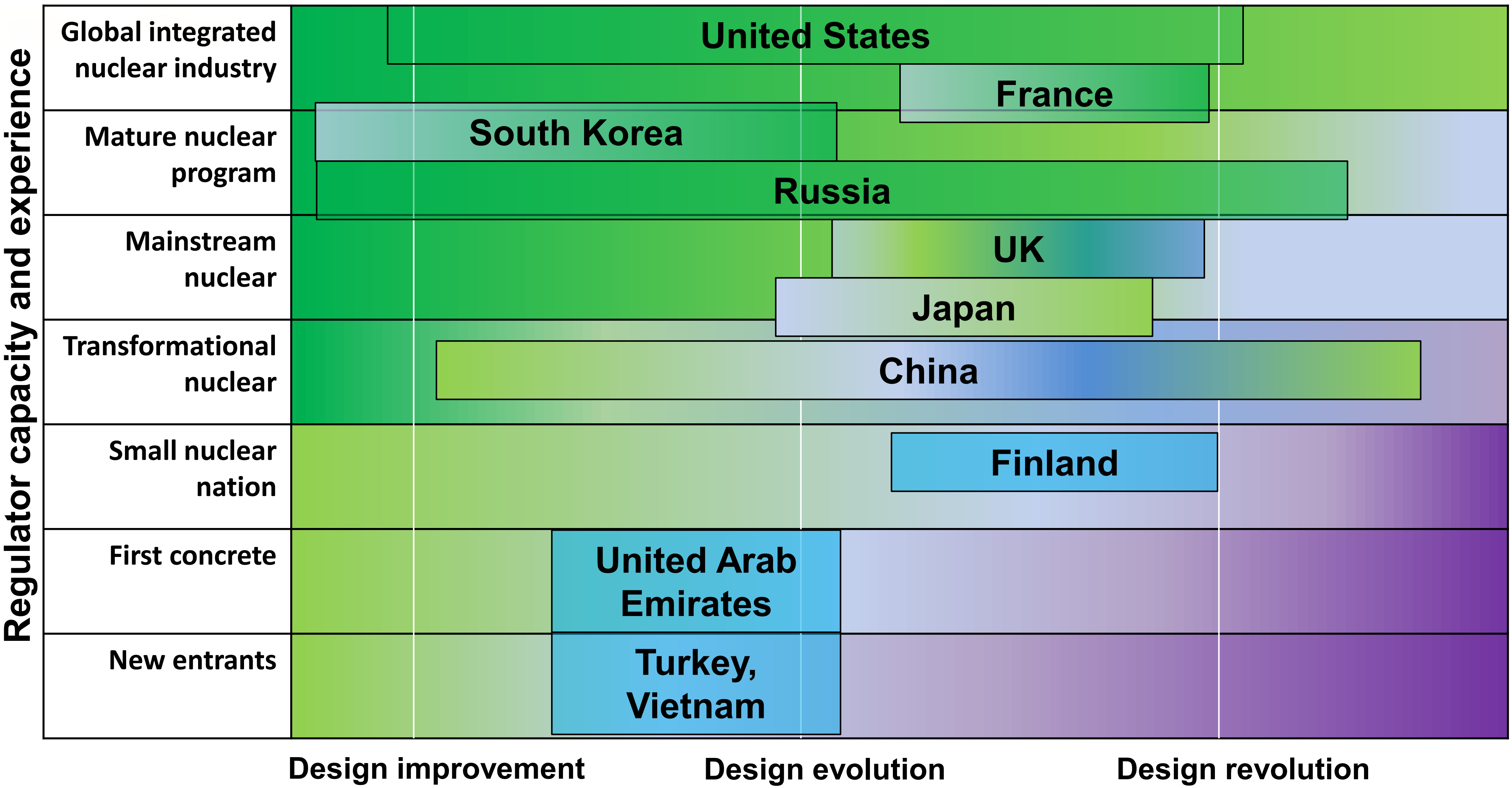
Major Benefits

- Simplicity of design
- Factory build benefits
- Flexibility: financing, siting, sizing,
- End-use applications: creating optionality
- Lower per plant capital cost – cash flow/lower risk
- Siting diversity
- Grid, mini-grids, or remote sites

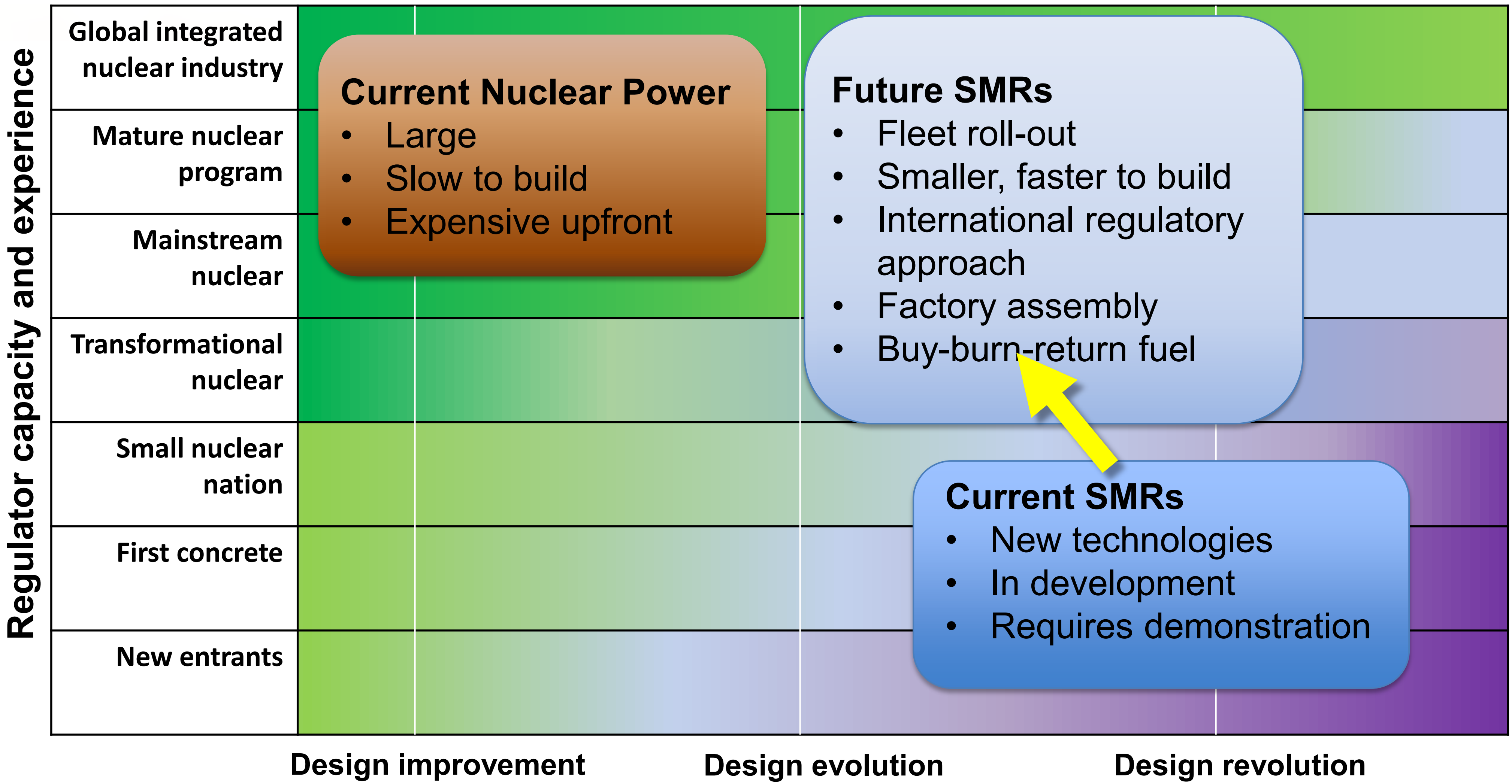
Client View: Attractive characteristics

- Established PWR technologies
- Minimal fuel movement
- Replacement: brownfield coal sites
- Remote deployment
- Dry cooling
- Reduced regulatory burden

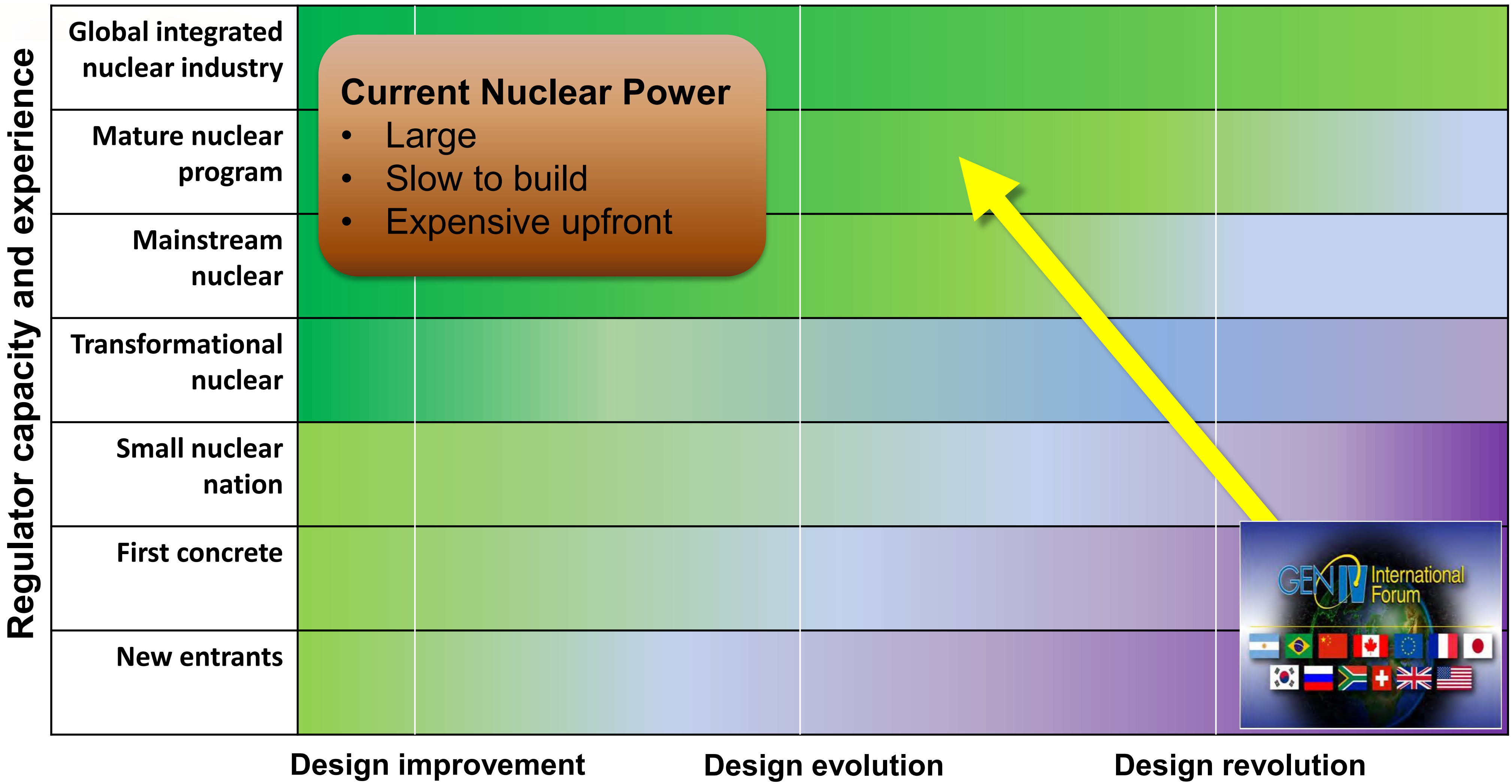
Countries and differences in experience.



Reactors and the developmental risk space

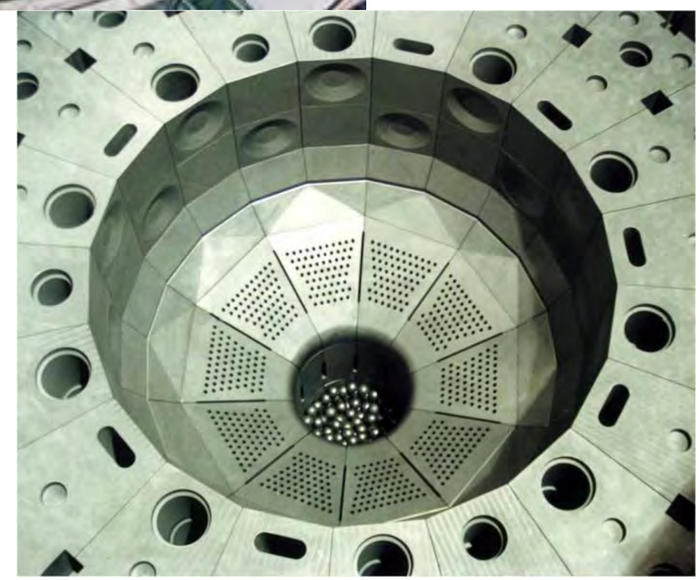


Gen-IV and the developmental risk space



Implementation strategies

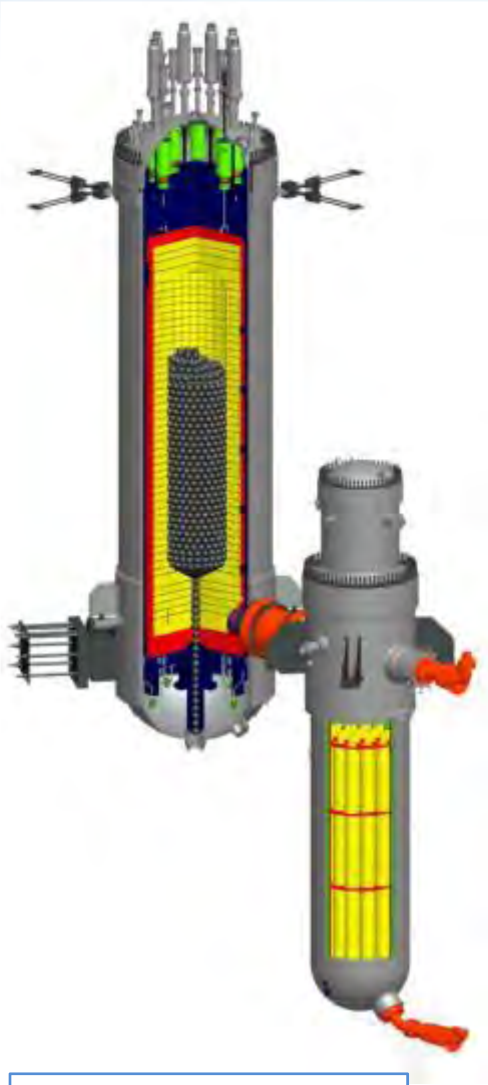
HTR-PM



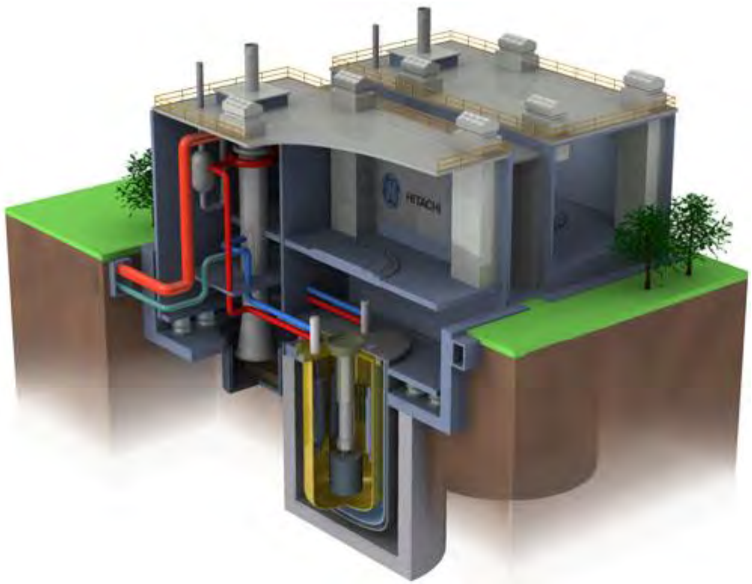
HTR-10

Implementation strategies

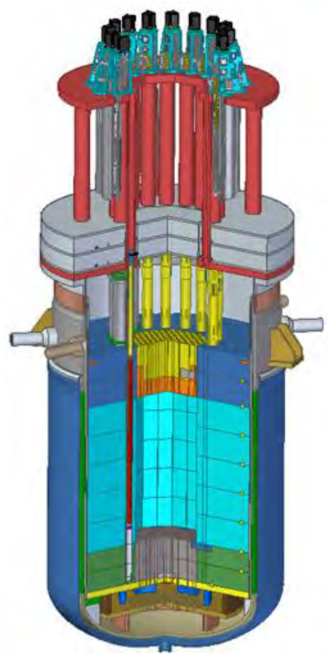
Future Gen IV SMRs



HTR-PM (China)



PRISM (GE-Hitachi)



Molten Salt Reactor
Pebble Fuel (SINAP)

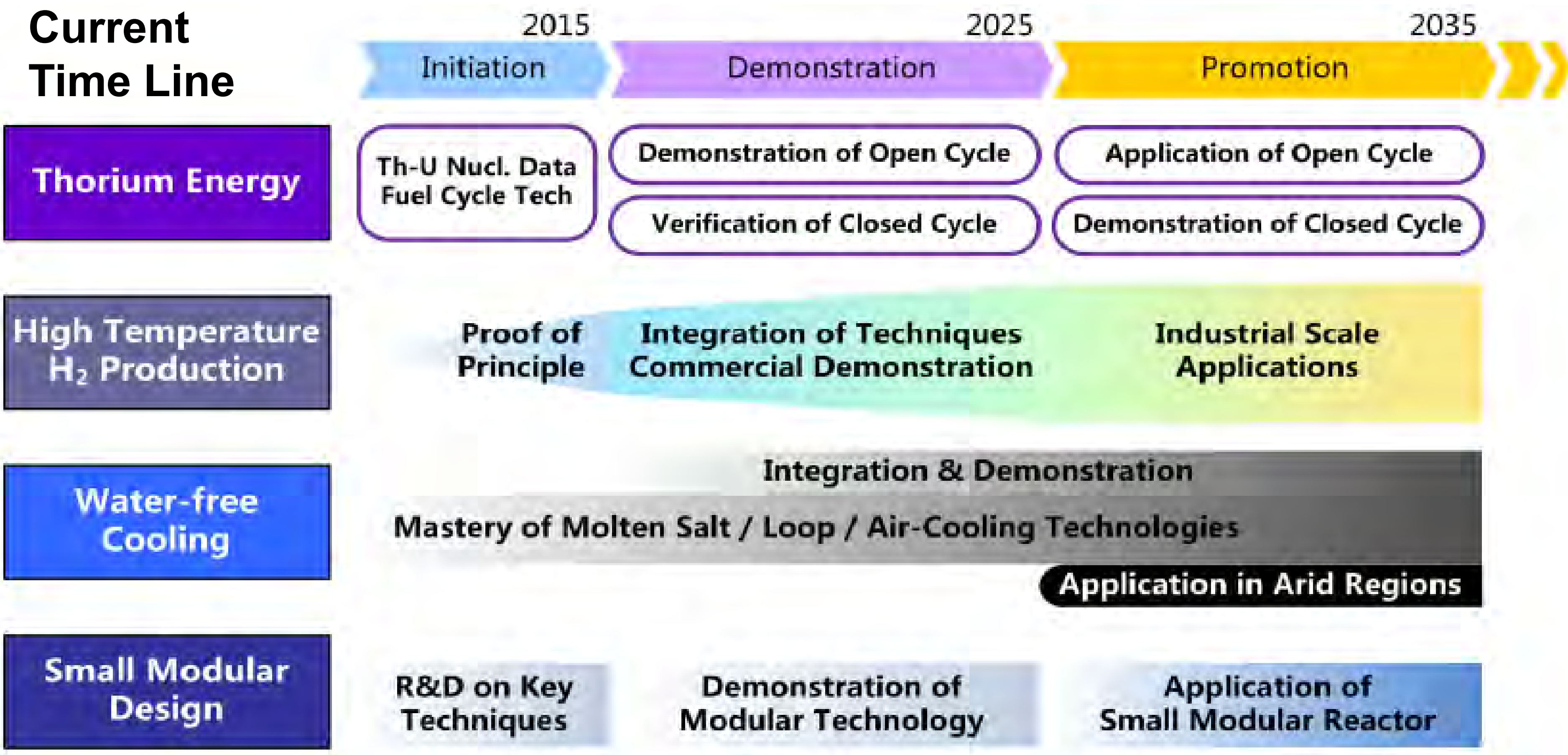
ANSTO and SINAP collaboration

Signing of ANSTO – SINAP MOU 2012

SINAP TMSR Project

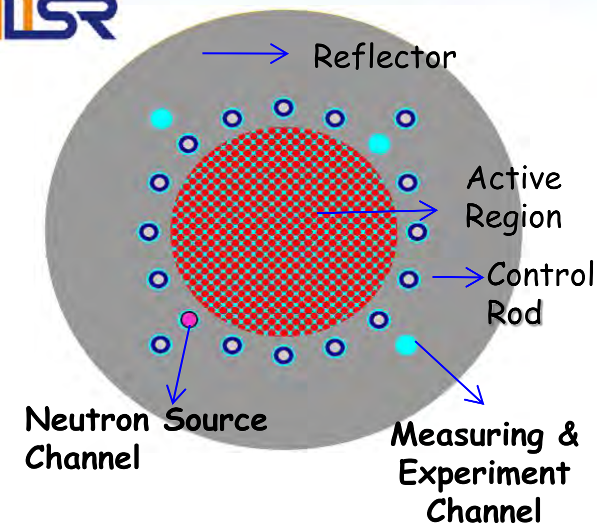
- Started in 2011: Chinese Academy of Sciences (CAS)
- Concept: “traditional”, liquid fueled, graphite moderated
- Staff numbers: 10X
- SINAP Emerging Mission: Accelerator driven systems

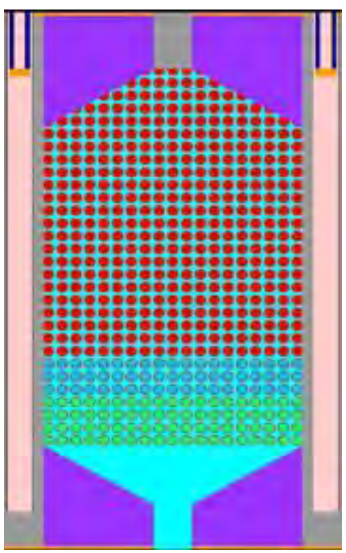
SINAP TMSR Project



Open cycle using pebble type solid fuel; closed cycle using molten salt fuel

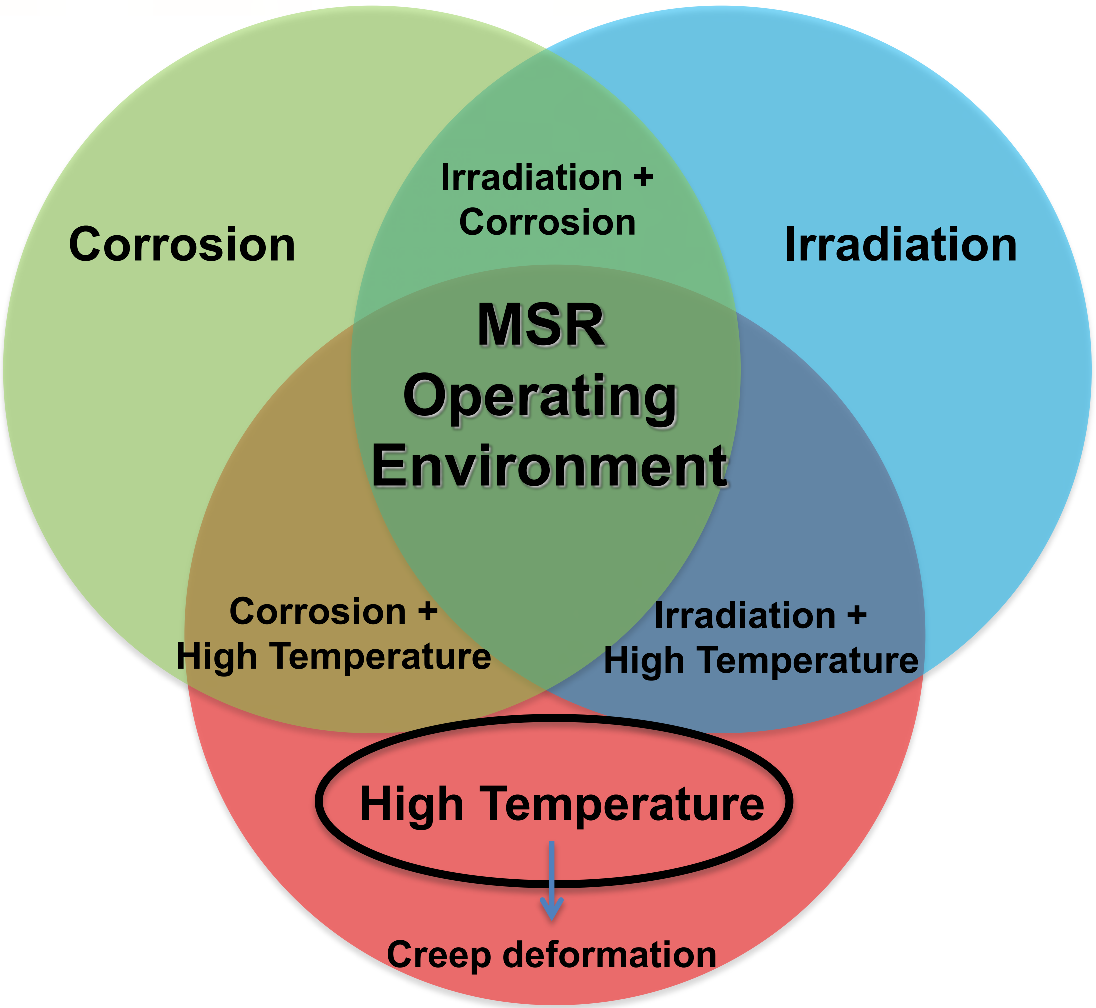
SINAP to start TMSR-SF1 in 2016





- 10 MW thermal
- 14,650 6cm dia. TRISO pebbles
- Primary coolant: 2LiF-BeF_2
- Secondary coolant: FLiNaK
- Operating Temperature: 628 ℃
- U-235 enrichment: 17.08 % (13.1 kg)

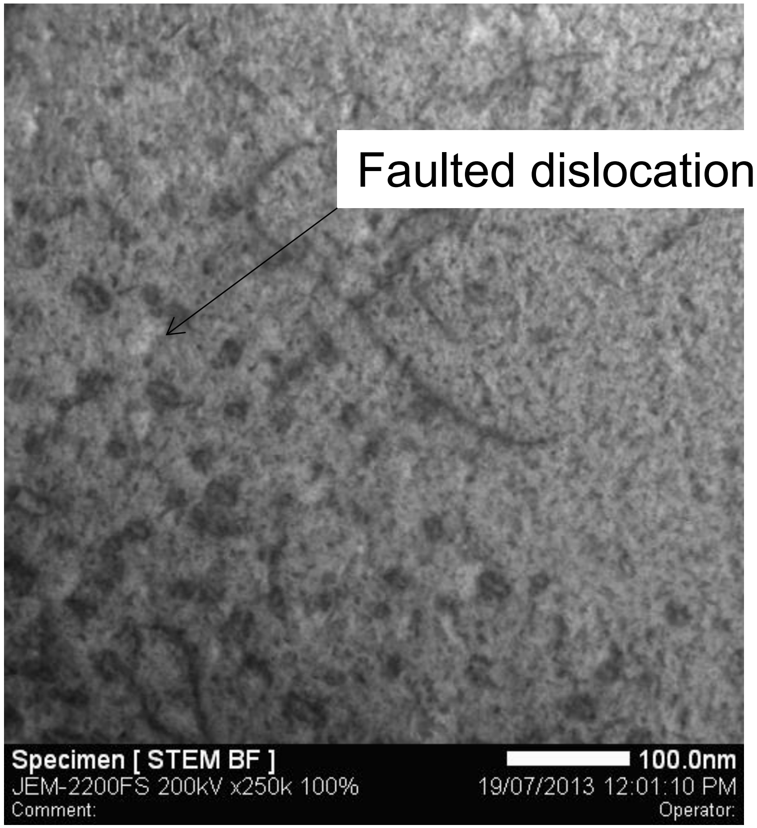
ANSTO-SINAP JRC

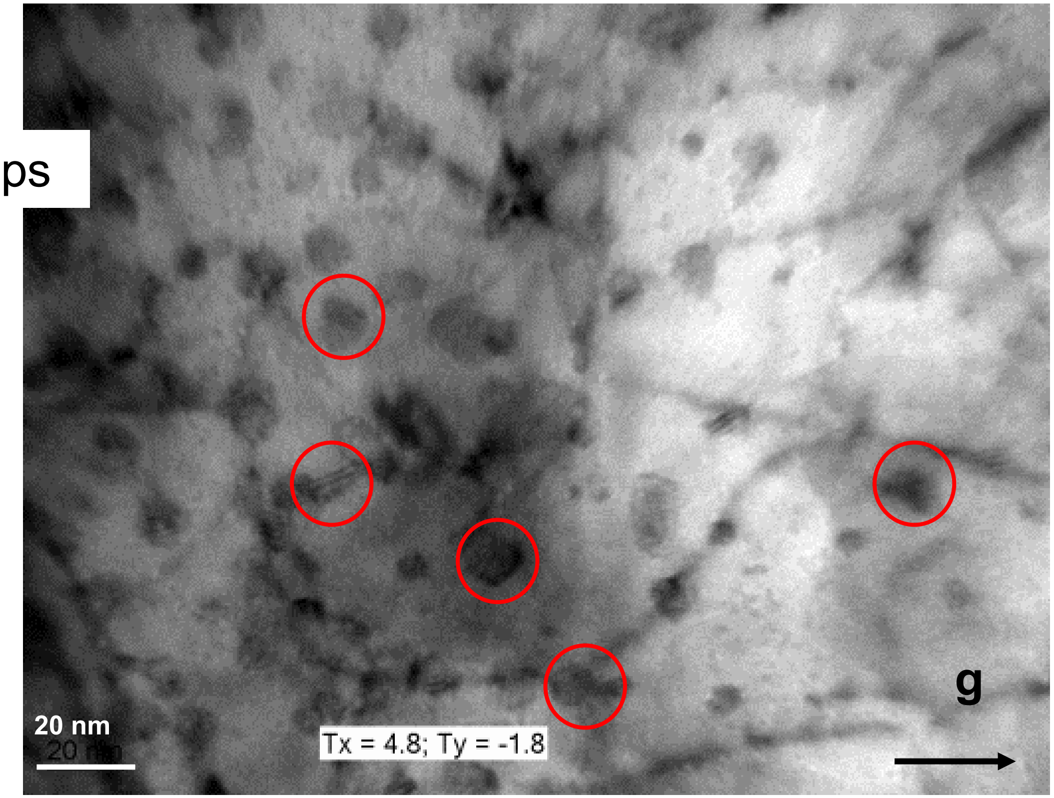


Requirements of MSR structural materials:

- Operating temperatures of 630-700 ^{o}C
- Corrosive molten fluoride salt (FLiNaK; FLiBe)
- Neutron radiation
- 0.6 MPa pressure
- 30 yrs reactor design life

JRC – Radiation Effects



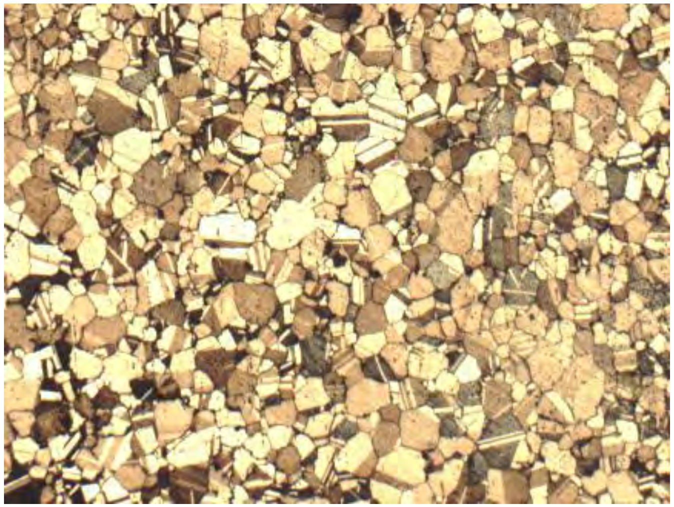
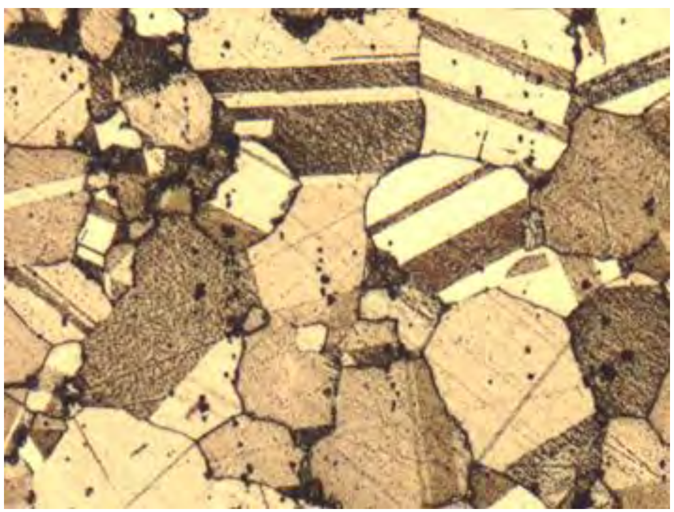


ZA [-112] 2B (-11-1)

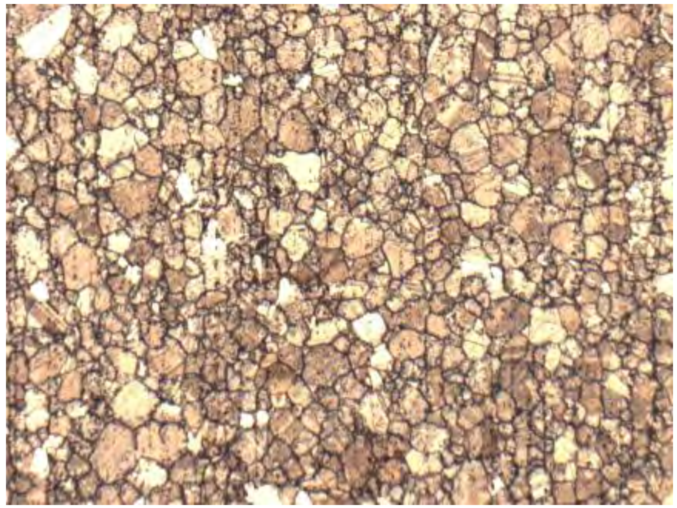
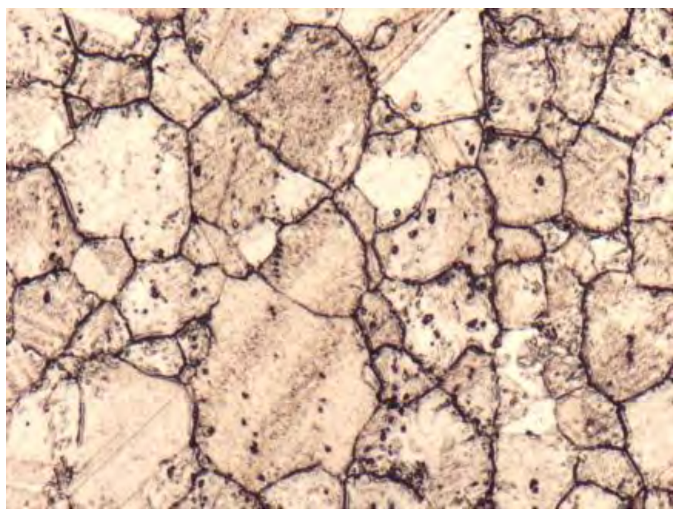
- Loops near dislocations fringed – possibly faulted
- Isolated loops have uniform grey contrast – unfaulted?

JRC – Corrosion Studies

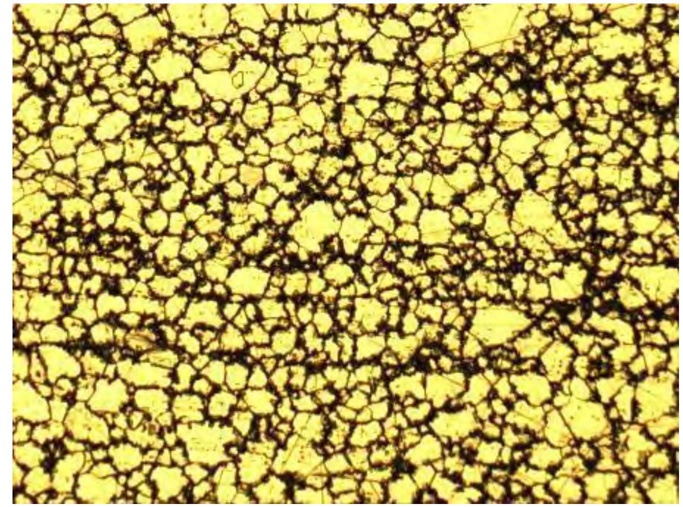
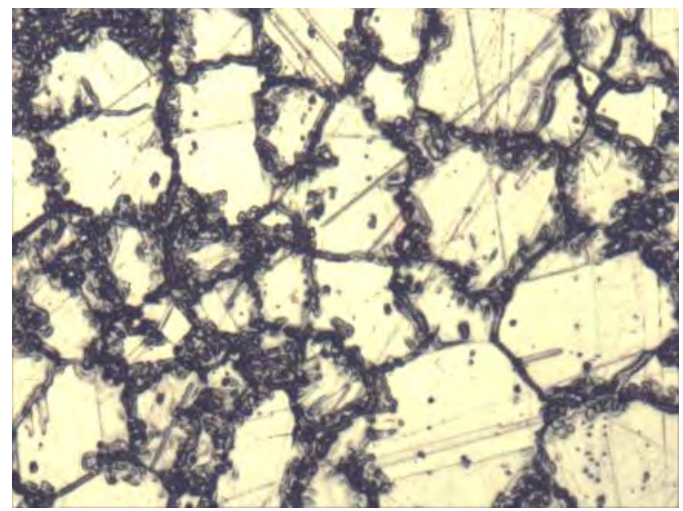
10 hour salt
Etch

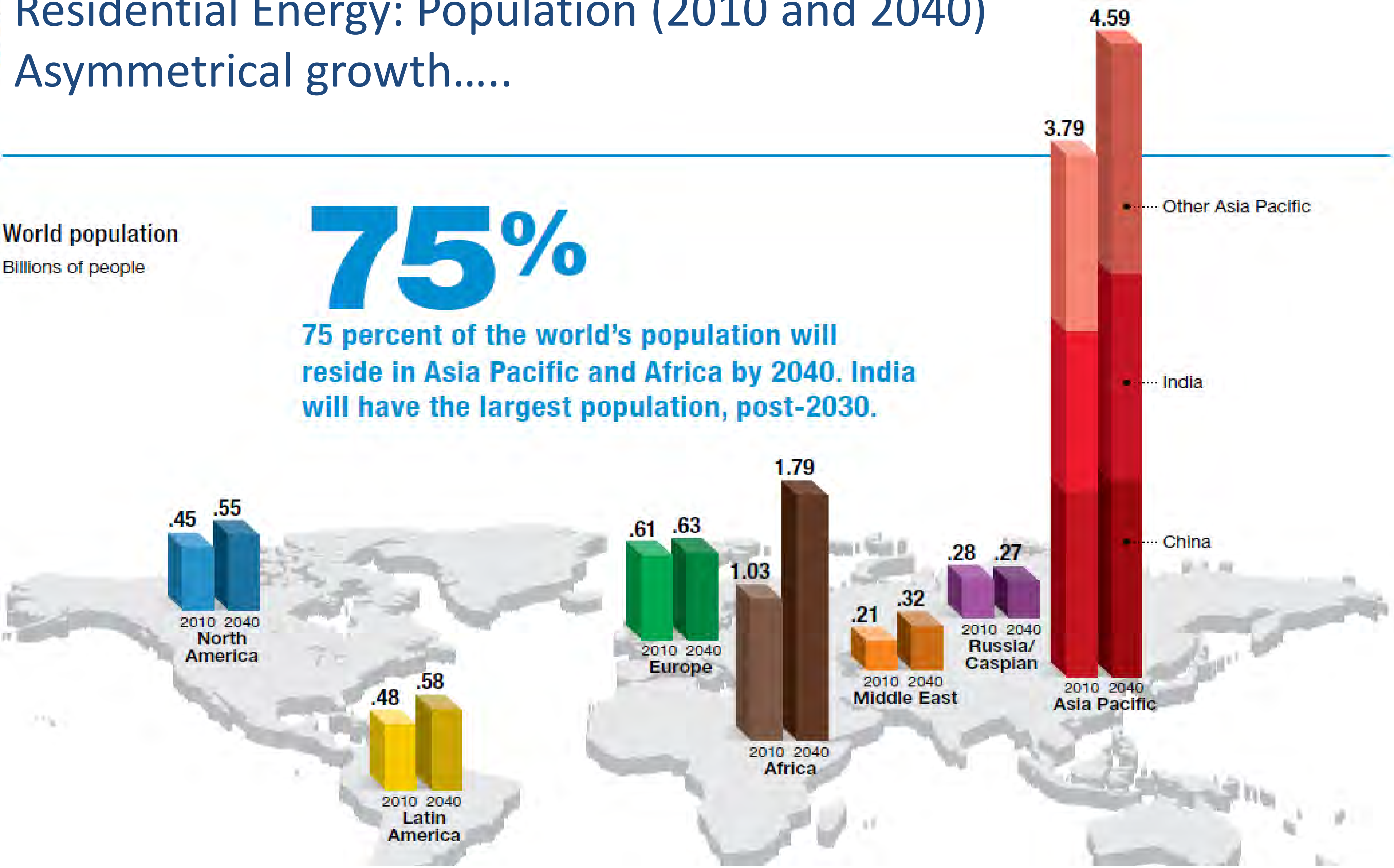
100 hour salt
Grain boundary (GB) attack

200 hour salt
GB electrochemical attack

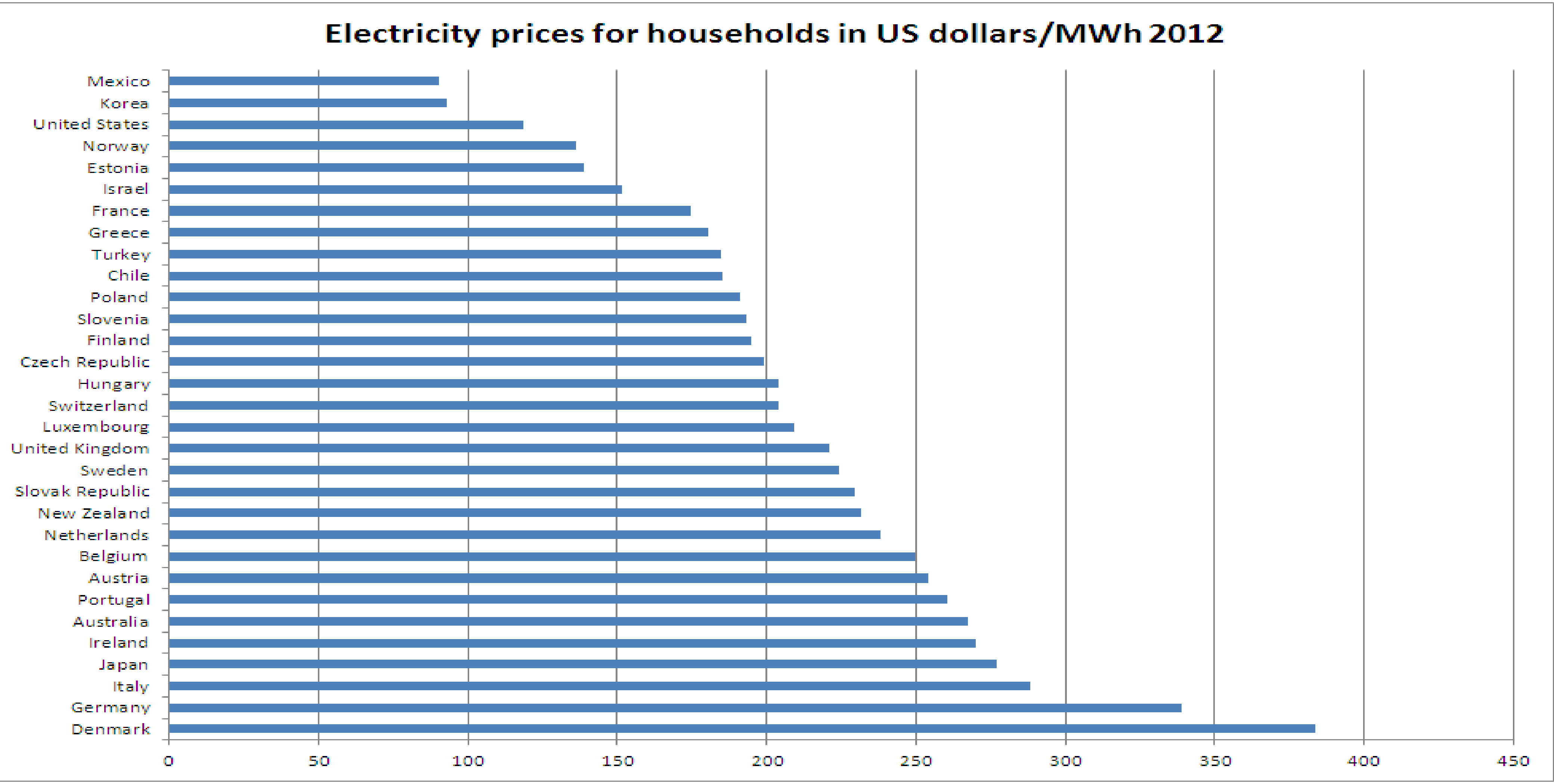



Residential Energy: Population (2010 and 2040) Asymmetrical growth…..



Source: Exxon Mobil Energy Scenarios 2013

High Price Destination



Source: AEMC Price Trends Report, 2013

Reasons to Stay Involved

- Global energy demand: asymmetrical growth
- Nuclear will play: Energy density, fuel security, CO_2
- Short to medium term nuclear options: “SMR”
- Medium to long term: Generation IV

- Beyond sovereignty: towards a global model
- Strategic view of the fuel cycle
- Being relevant in our region: or not?


ANSTO making sense of nuclear

Thank You

Acknowledgments: Mark Ho, Greg Lumpkin and Jarrod Powell (ANSTO)

Australian Government

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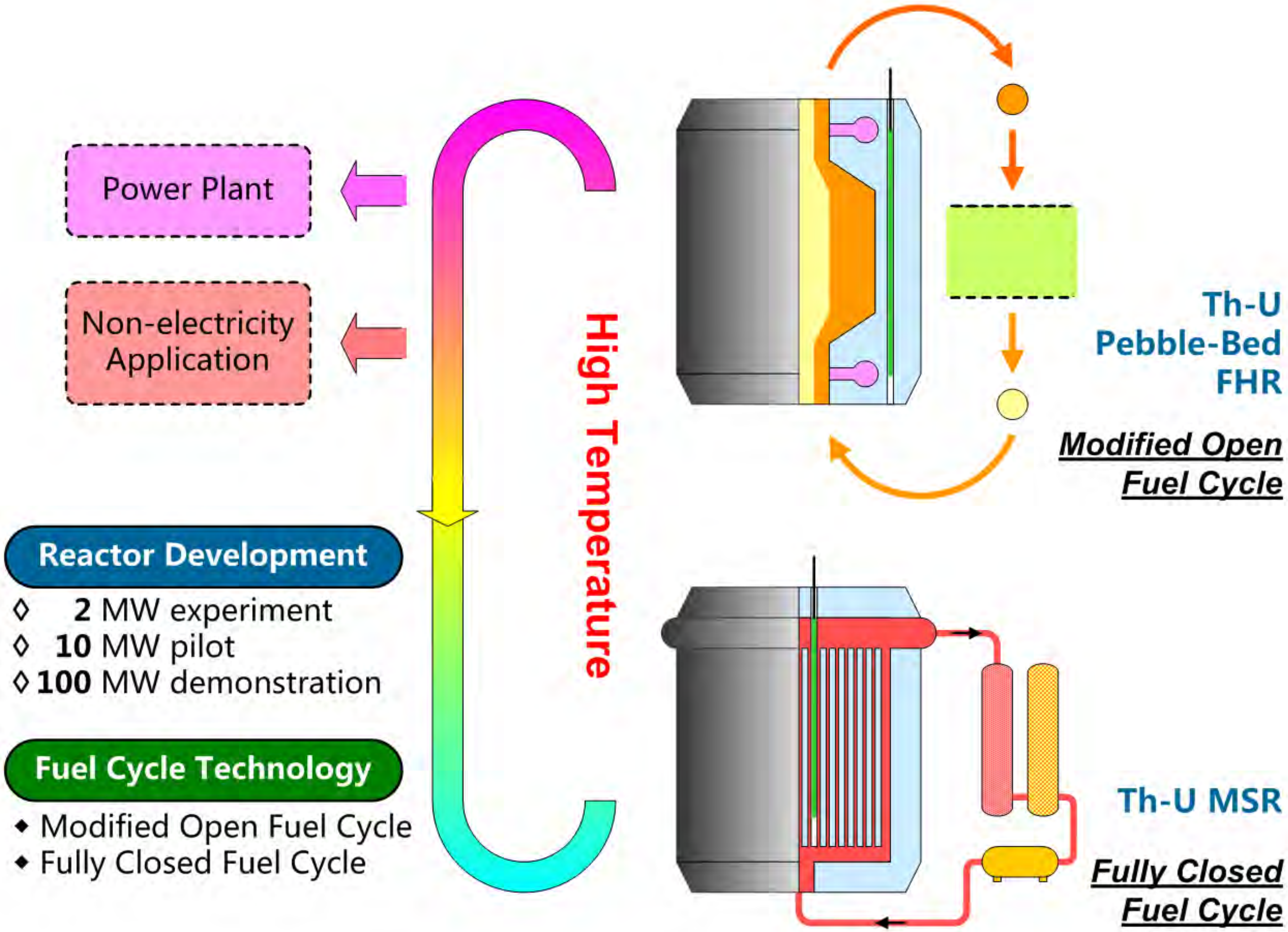
Questions / Feedback

SINAP TMSR Project



Scheme of TMSR Developing Strategy

Initial concept was the closed, molten salt fueled design based on the Oak Ridge MSRE project circa 1960-1970

Technical issues (e.g., salt purity and loop development) have led to advancement of the open cycle, pebble bed solid fuel design

JRC – Atomistic Simulations

Faulted vacancy loop formed as a result of interaction with pre-existing dislocation