GEN IV International Forum[SM]

ATOMS FOR PEACE
THE NEXT GENERATION

Dr. John E. Kelly

U.S. Department of Energy, Office of Nuclear Energy

September 29, 2016

NEA Nuclear Energy Agency

cea DE LA RECHERCHE À L'INDUSTRIE

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

NATIONAL NUCLEAR LABORATORY

Argonne NATIONAL LABORATORY

INL Idaho National Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

NPS PRAESTANTIA PER SCIENTIAM

MEET THE PRESENTER

Dr. John E. Kelly is the Deputy Assistant Secretary for Nuclear Reactor Technologies in the U.S. Department of Energy's Office of Nuclear Energy. His office is responsible for the civilian nuclear reactor research and development portfolio, which includes programs on Small Modular Reactors, Light Water Reactor Sustainability, and Advanced (Generation IV) Reactors. His office also is responsible for the design, development, and production of radioisotope power systems, principally for missions of the U.S. National Aeronautics and Space Administration. In the international arena, Dr. Kelly is the immediate past chair of the Generation IV International Forum (GIF) and the former chair of the International Atomic Energy Agency's Standing Advisory Group on Nuclear Energy.
Prior to joining the Department of Energy in 2010, Dr. Kelly spent 30 years at Sandia National Laboratories, where he was engaged in a broad spectrum of research programs in nuclear reactor safety, advanced nuclear energy technology, and national security. In the reactor safety field, he led efforts to establish the scientific basis for assessing the risks of nuclear power plant operation and specifically those risks associated with potential severe accident scenarios. His research focused on core melt progression phenomena and this led to an improved understanding of the Three Mile Island accident and, more recently, the Fukushima Daiichi accident. In the advanced nuclear energy technology field, he led efforts to develop advanced concepts for space nuclear power, Generation IV reactors, and proliferation-resistant and safe fuel cycles. These research activities explored new technologies aimed at improving the safety and affordability of nuclear power.

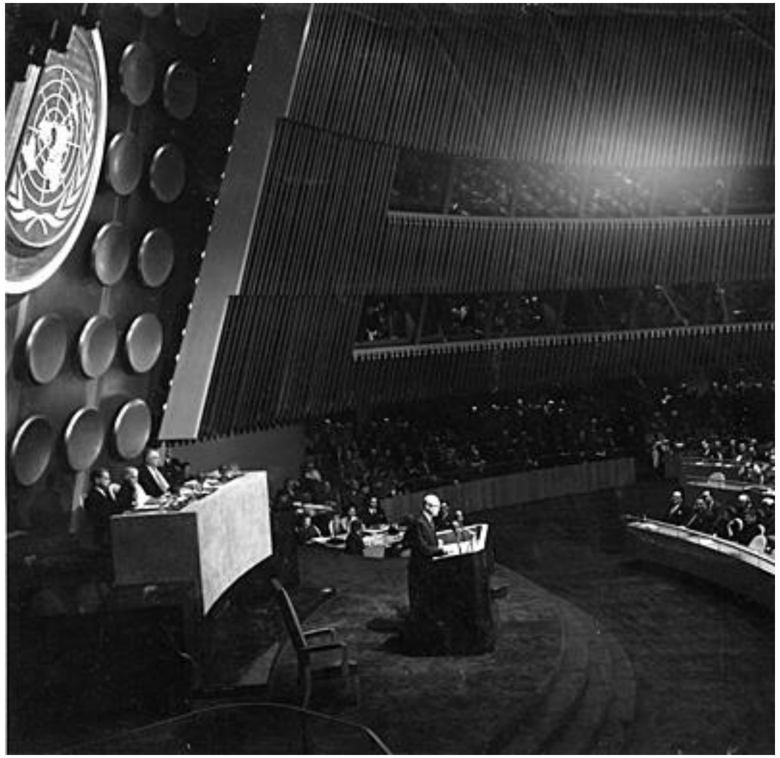
Dr. Kelly received his B.S. degree in nuclear engineering from the University of Michigan in 1976 and his Ph.D. in nuclear engineering from the Massachusetts Institute of Technology in 1980.

Email: JohnE.Kelly@nuclear.energy.gov

OUTLINE

- Atoms for Peace and the History of Civilian Nuclear Power
- Today's Nuclear Reactor Technology
- Generation IV Reactors
- Summary

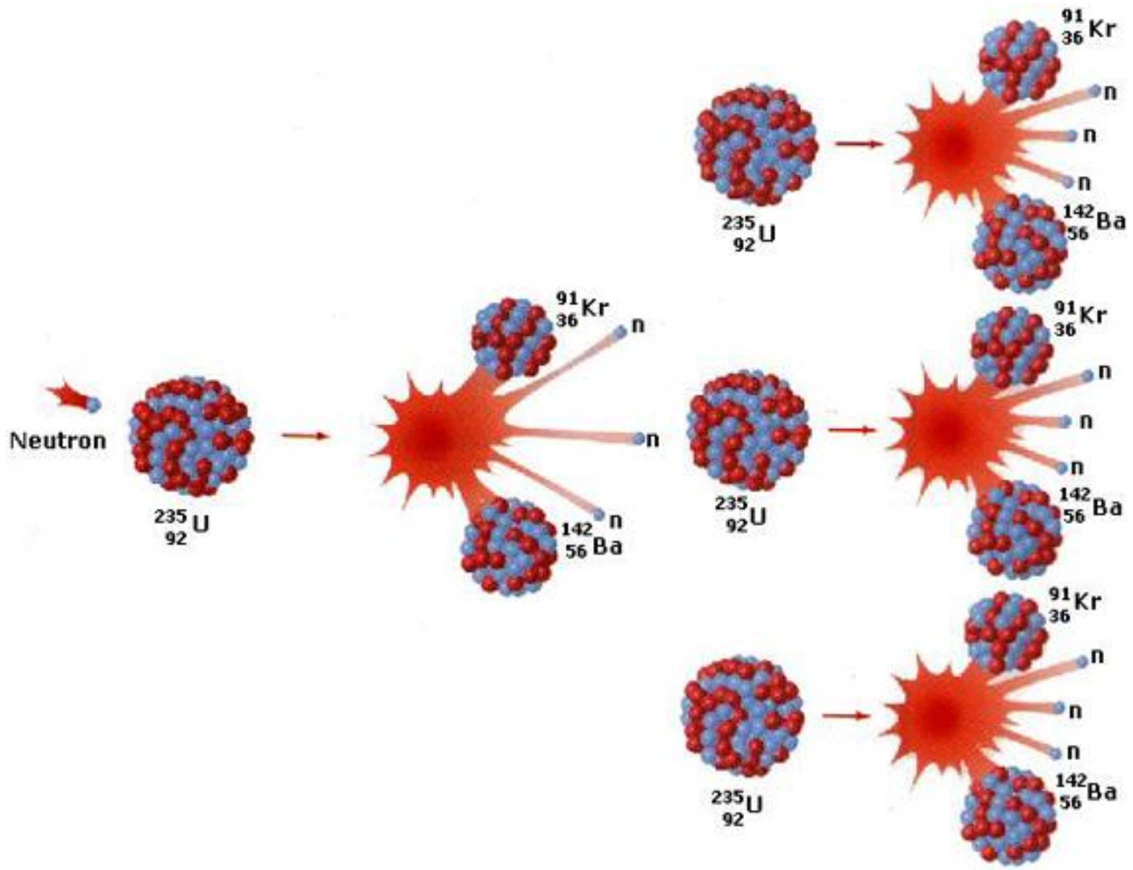
ATOMS FOR PEACE



"Peaceful power from atomic energy is no dream of the future. That capability, already proved, is here – now – today."

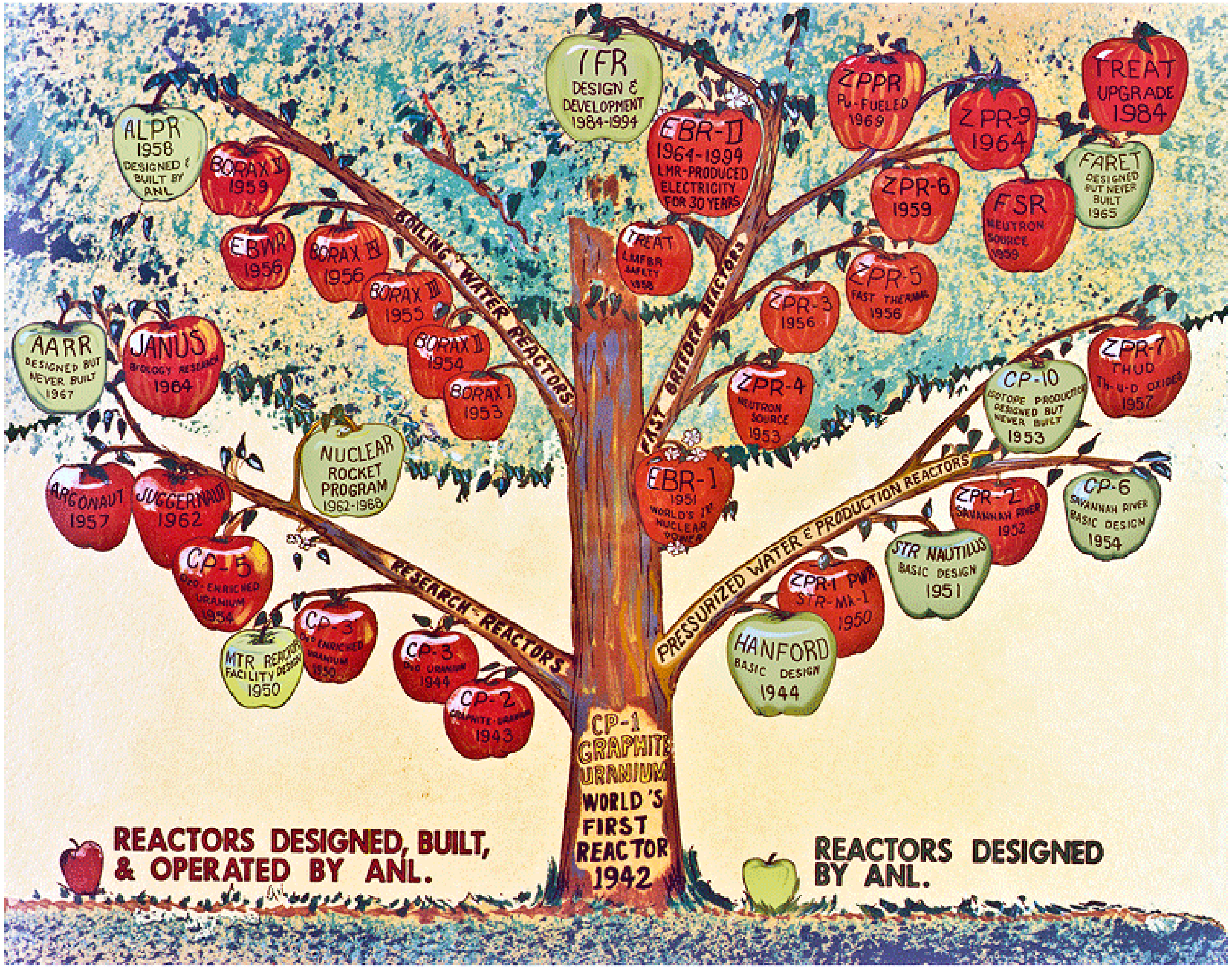
~ President Dwight D. Eisenhower, December 8, 1953, to the 470th Plenary Meeting of the United Nations General Assembly

NUCLEAR FISSION DISCOVERED IN 1938



- Each uranium fission releases a large amount of energy and 2.5 neutrons (on average) that can then create a chain reaction.
- In nuclear reactors, the chain reaction is controlled so that the number of neutrons created by fission equals the number absorbed in fuel, control rods, and other materials.

EARLY REACTOR DESIGNS



GEN IV International Forum℠

09-50898-01n

Generation I

Big Rock Point, GE BWR

Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Generation II

Diablo Canyon, Westinghouse PWR

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville 1-2** (PWR)
- **Fukushima II 1-4** (BWR)
- **Grand Gulf** (BWR)
- **Kalinin** (PWR/VVER)
- **Kursk 1-4** (LWGR/RBMK)
- **Palo Verde** (PWR)

Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

Evolutionary designs

- **ABWR** (GE-Hitachi; Toshiba BWR)
- **ACR 1000** (AECL CANDU PHWR)
- **AP1000** (Westinghouse-Toshiba PWR)
- **APR-1400** (KHNP PWR)
- **APWR** (Mitsubishi PWR)
- **Atmea-1** (Areva NP -Mitsubishi PWR)
- **CANDU 6** (AECL PHWR)
- **EPR** (AREVA NP PWR)
- **ESBWR** (GE-Hitachi BWR)
- **Small Modular Reactors**
  - B&W mPower PWR
  - CNEA CAREM PWR
  - India DAE AHWR
  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

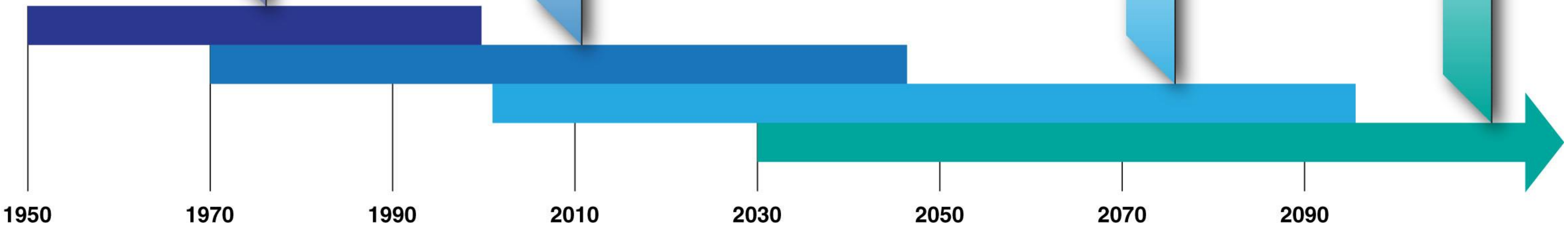
Generation IV

Safe
Secure
Sustainable
Competitive
Versatile

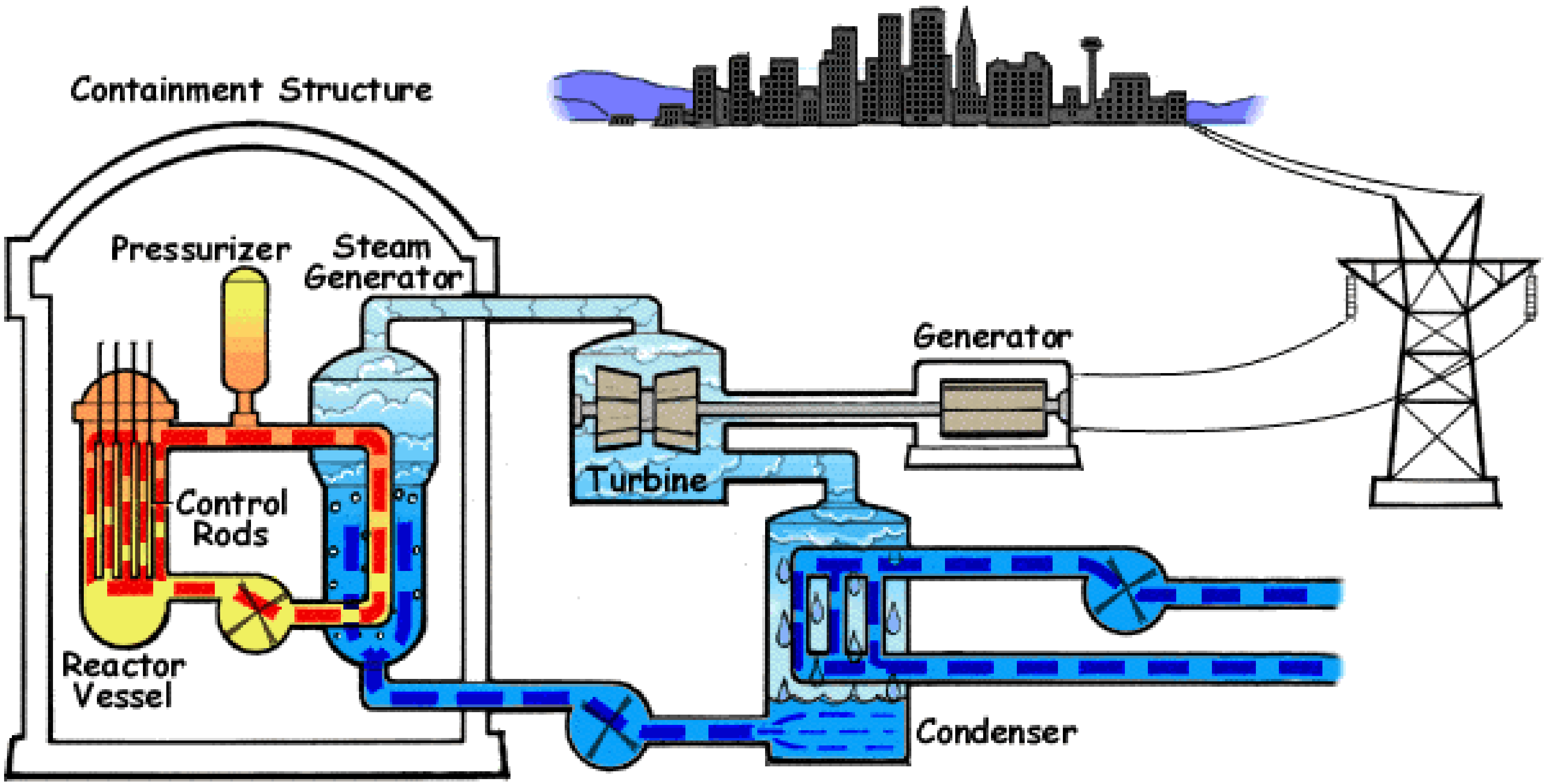
Arriving ~ 2030

Innovative designs

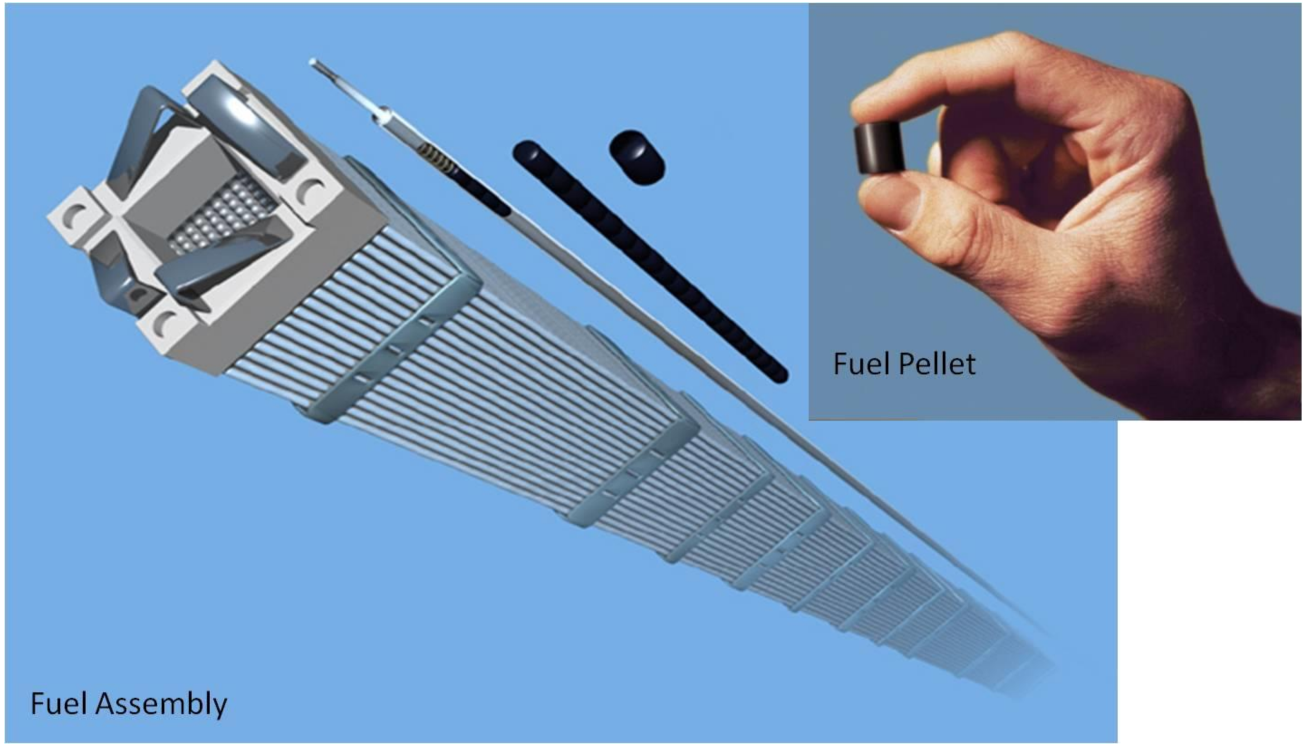
- **GFR** gas-cooled fast reactor
- **LFR** lead-cooled fast reactor
- **MSR** molten salt reactor
- **SFR** sodium-cooled fast reactor
- **SCWR** supercritical water-cooled reactor
- **VHTR** very high temperature reactor



BASICS OF A NUCLEAR POWER PLANT



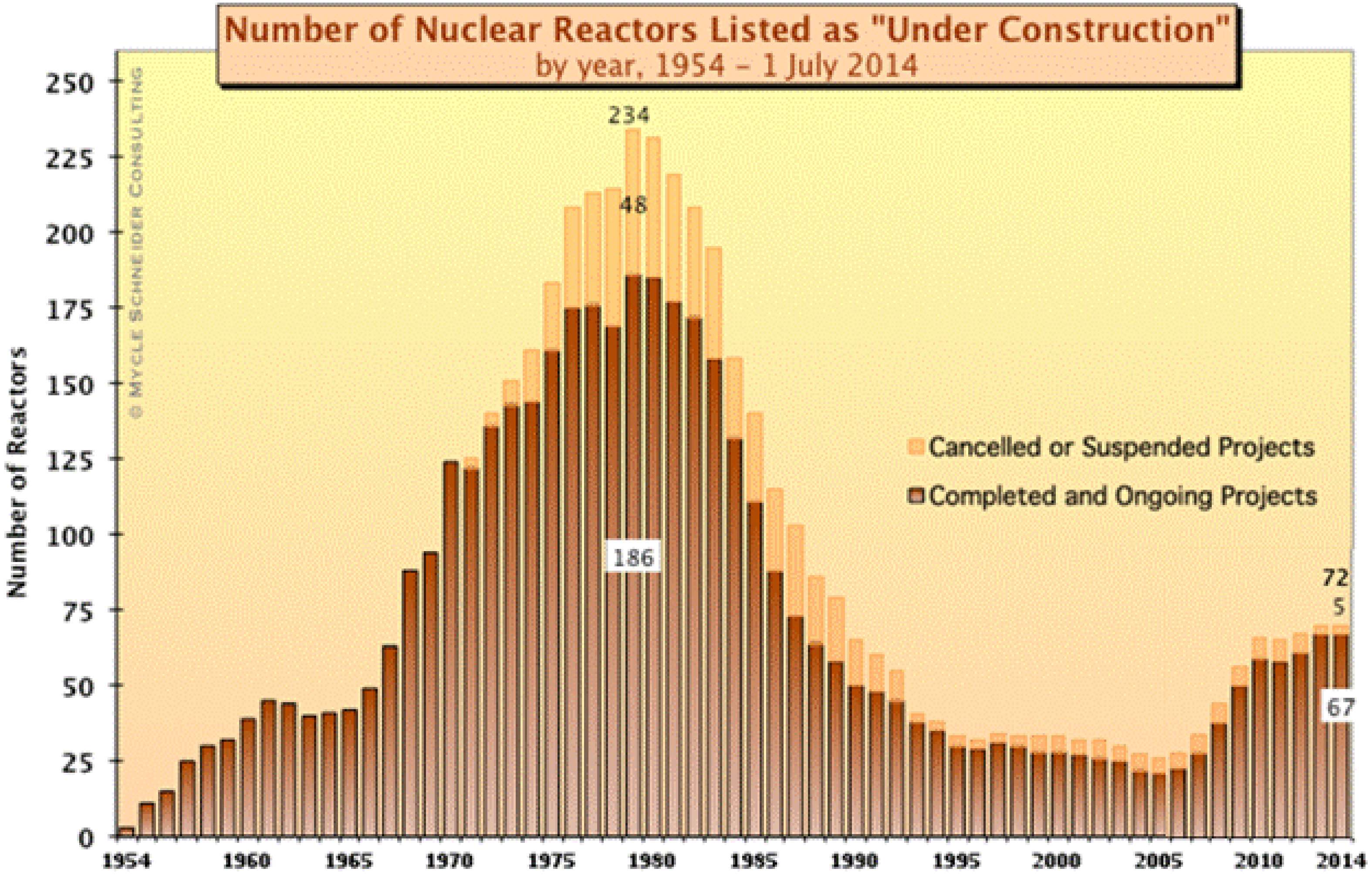
URANIUM ENERGY DENSITY IS HUGE



One uranium fuel pellet (~7 gm) in a commercial light water reactors has about as much energy available as:

- 1400 cubic meters of oil
- One metric tonne of coal
- 480 cubic meters of natural gas

NUCLEAR POWER PLANTS BUILT WORLDWIDE



Source: World Nuclear Report

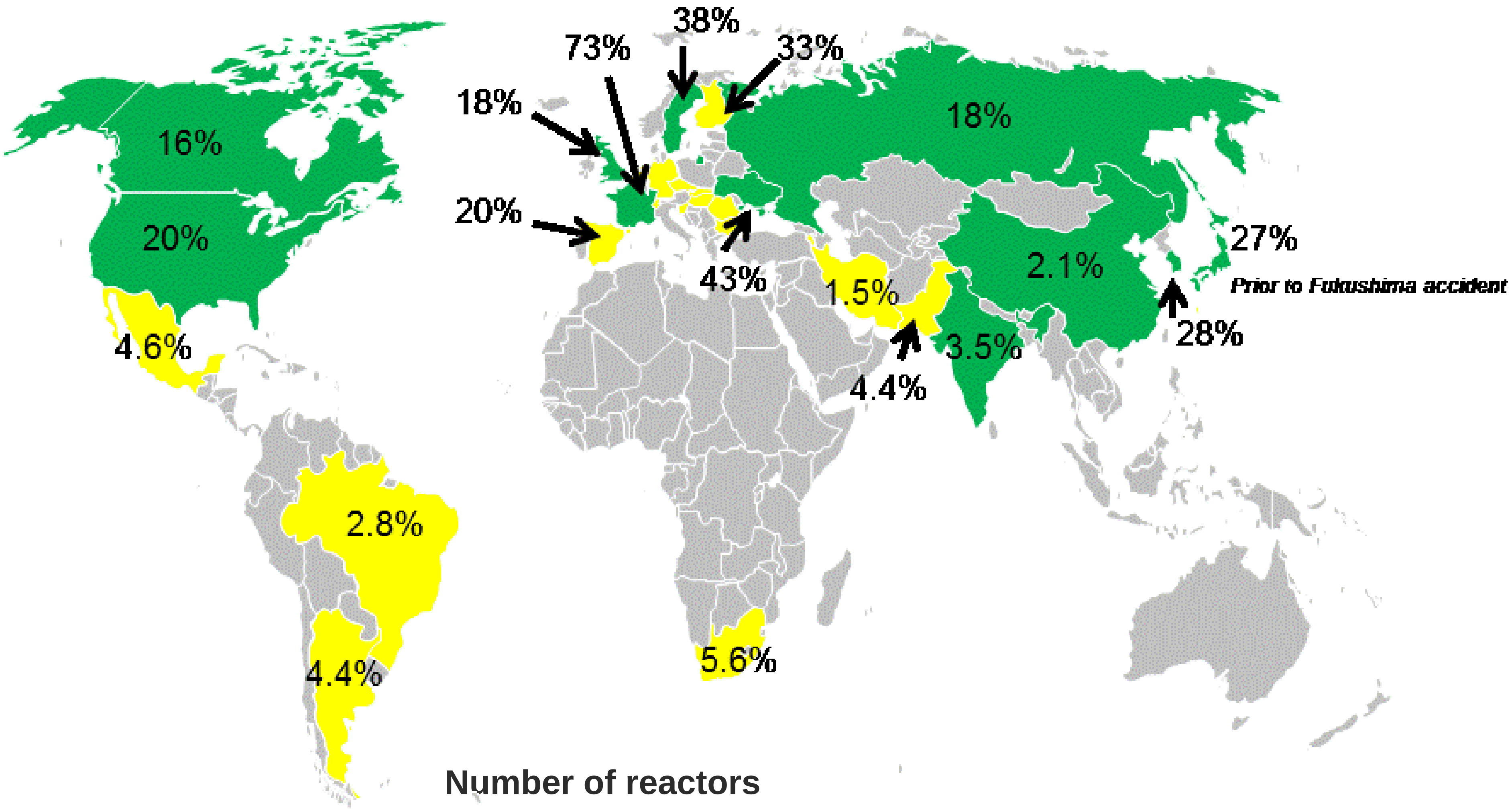
DRIVERS FOR THE FIRST WAVE OF REACTORS

- **Encouraging drivers**
  - Re-emerging Economies Required Increased Energy in Post World War II Period
  - The Oil Crises of the 1970s
  - Strong Government Backing

- **Neutral drivers**
  - Acid Rain
  - Air Pollution
  - 1971- Inadvertent Climate Modification. Report of the Study of Man's Impact on Climate

- **Discouraging drivers**
  - High Interest Rates
  - Fear of Radiation
  - Fear of Nuclear Weapons
  - Three Mile Island Accident
  - Chernobyl Accident
  - Waste Management Impasse

NUCLEAR POWER TODAY



Number of reactors

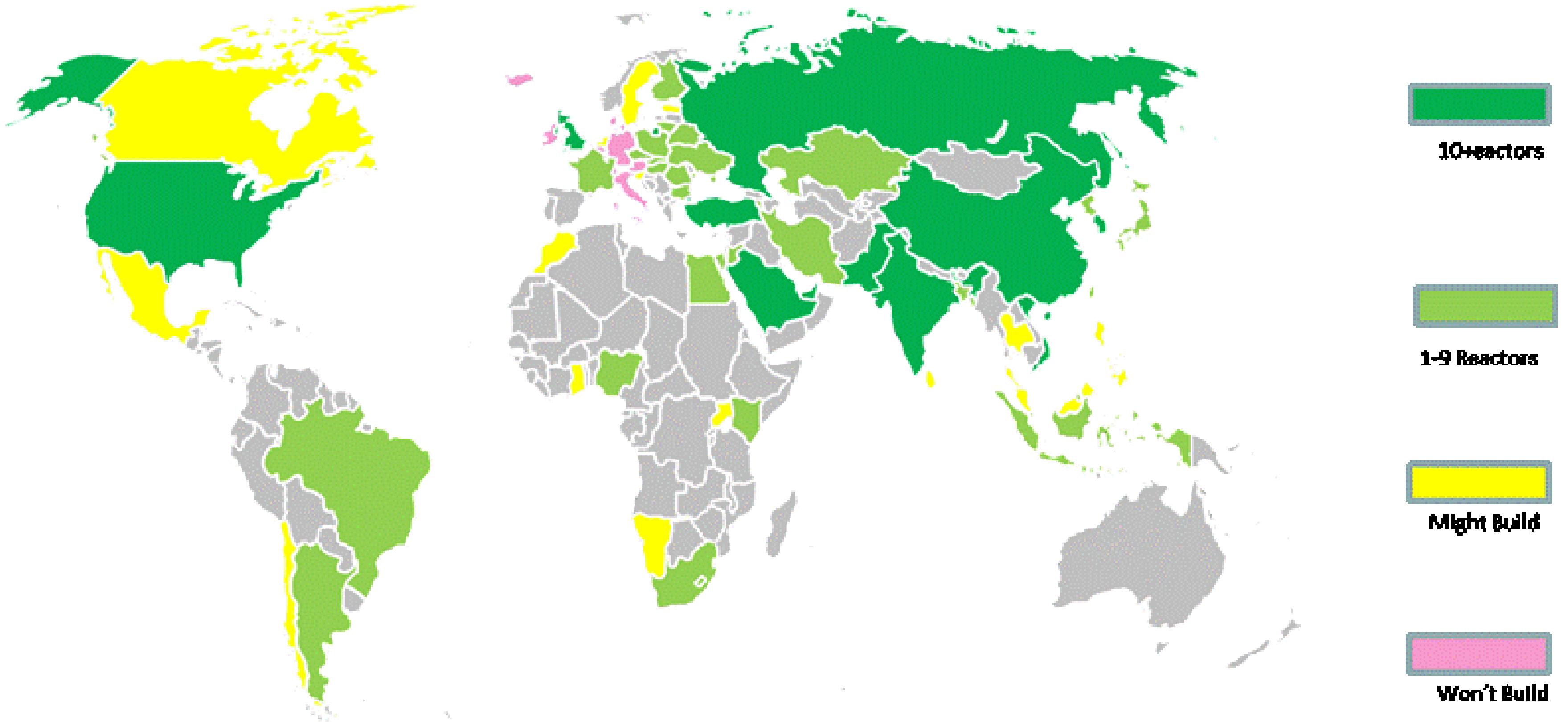
(green)	10+
(yellow)	1-9

~ Source: IAEA information & news reports

CURRENT DRIVERS FOR NUCLEAR POWER

- Energy security
  - Nuclear shelters countries from imports of costly fossil fuels
  - Replacing retired nuclear or coal generation plants
- Economic incentives
  - Nations rich in fossil fuel would prefer to export those resources and use nuclear for domestic electricity production
- Environmental protection
  - Replacing coal with nuclear can alleviate air pollution problems
- Climate change concerns
  - Nuclear is the “emission-free” base load generation technology
  - Dry condenser cooling possible with small modular reactors when water usage is restricted

PLANS FOR REACTOR CONSTRUCTION



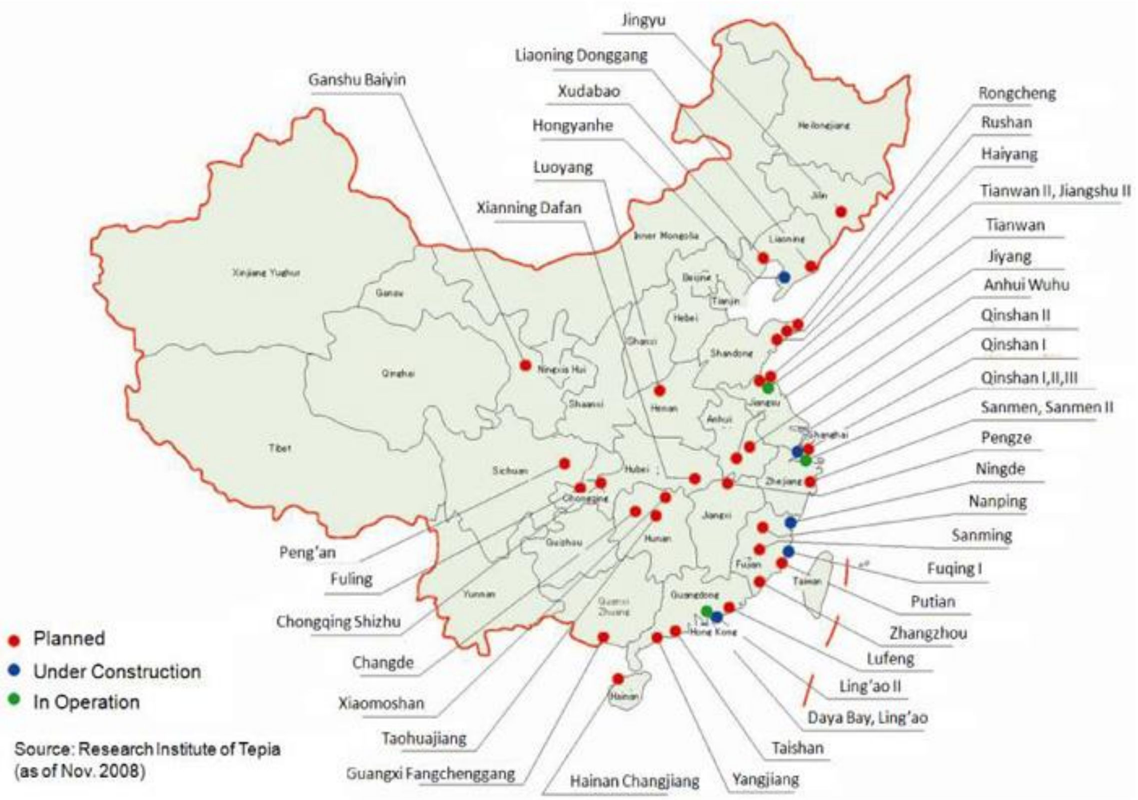
- 439 nuclear reactors operating in 30 countries (373 GWe capacity)
- 69 reactors currently under construction in 15 countries (24 in China)
- 172 reactors planned in 26 countries over next 8-10 years
- 309 reactors proposed in 35 countries over next 15 years

CHINA's NUCLEAR POWER EXPANSION

- Most of China's electricity is produced from fossil fuels
  - 2015 OECD/NEA data shows 73% fossil fuels (mostly coal), 19% hydro, 3% nuclear, and 5% renewables

- China has 34 nuclear power reactors in operation, 20+ under construction, and at least 179 planned or proposed for construction

- Additional reactors are planned to increase nuclear capacity
  - Goal is for 58 GWe by 2020, 150 GWe by 2030, and much more by 2050



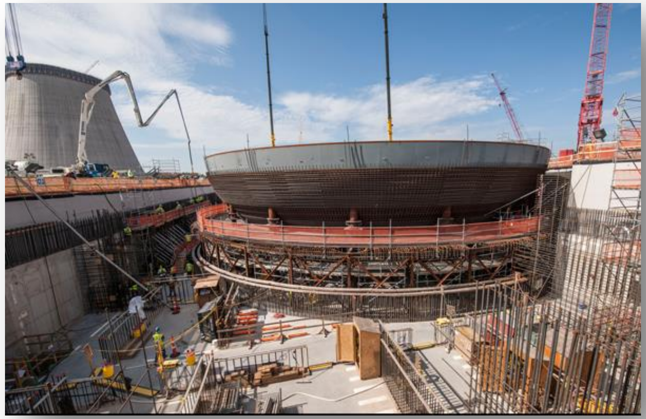
AP1000 Construction in China and the United States

China

Sanmen – May 2014
Source: SNPTC

Haiyang – May 2014
Source: State Nuclear Power Engineering

United States



VC Summer – June 2014
Source: SCE&G

Vogtle – July 2014
Source: Georgia Power Co.

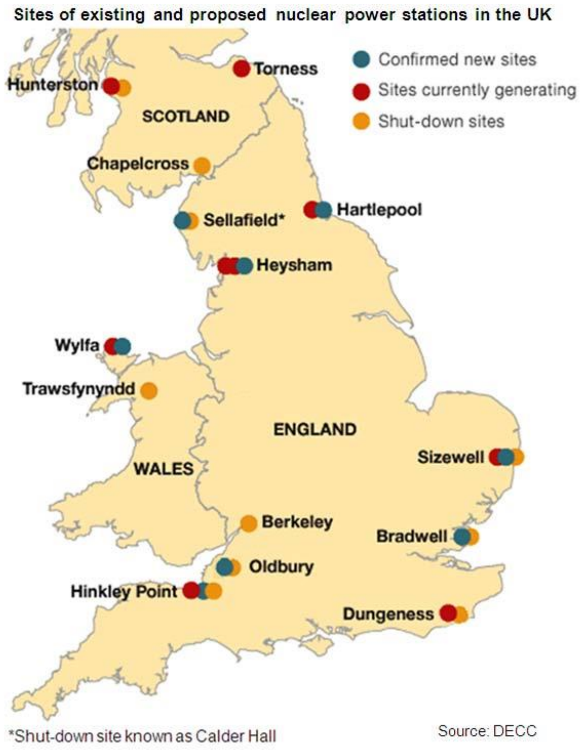
UK's REPLACEMENT PROGRAM

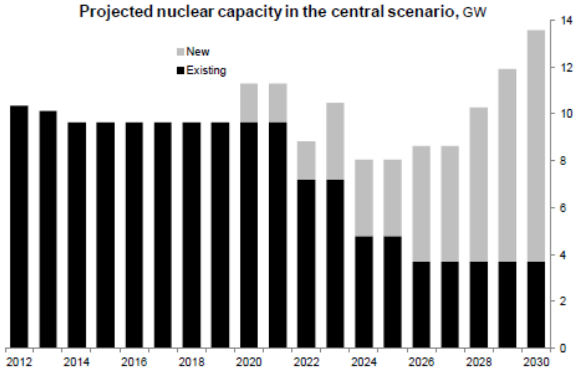
- *"The Government's preliminary view is that it is in the public interest to give the private sector the option of investing in new nuclear power stations….the Government believes that new nuclear power stations could make a significant contribution to tackling climate change" (2007 Energy White paper)*

- 15 reactors generating about 21 percent of the country's electricity; almost half will retire by 2025

- 11 reactors totaling 16GWe (150% of current nuclear capacity) planned to begin commercial operation by 2030

- Predicted new nuclear power could save on the order of £15 billion over next 40 years





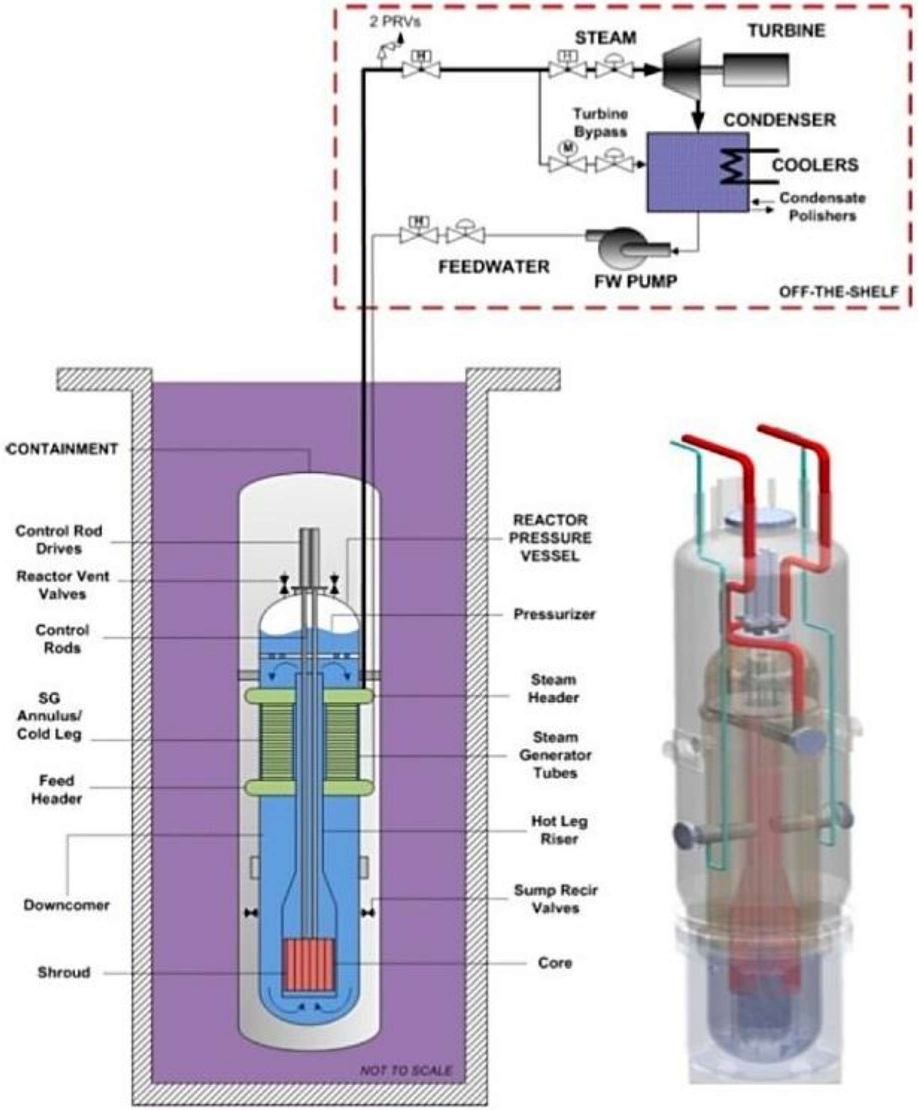
NUCLEAR NEWCOMER – UNITED ARAB EMIRATES

- Drastically increasing energy demand
  - Especially for water desalination
- Currently entirely dependent on natural gas and oil for domestic energy supply
  - Strong desire to reduce dependence while meeting growing energy needs
- Public opinion changing in favor of increased nuclear
  - 66% in favor in 2011
  - 82% in favor in 2012
- Four reactors currently under construction at the Barakah plant site
  - First unit expected to come on-line in 2017

Barakah plant under construction (*Source: UAE Interact*)

SMALL MODULAR REACTORS

- First mention of small modular reactors (SMRs) in the early 1980s
- Small (<300 MWe) and modular
- Factory fabrication and transportable
- Tremendous interest has been building since the early 2000s for commercialization of SMRs



BENEFITS OF SMRs

- **Safety Benefits:**
  - Passive decay heat removal by natural circulation
  - Simplified design eliminates/mitigates several postulated accidents
  - Below grade reactor sites
  - Potential for reduction in Emergency Planning Zone

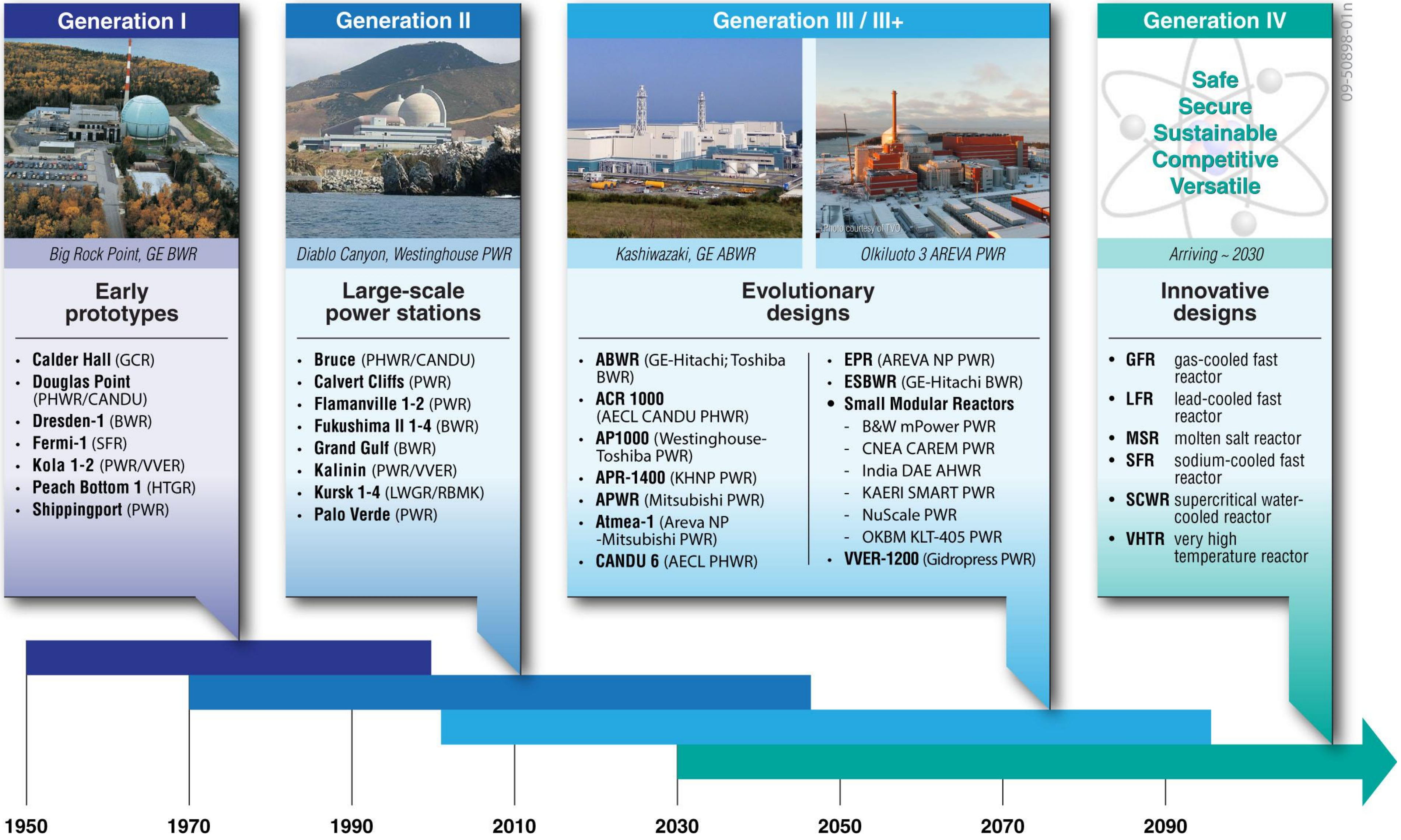
- **Economic Benefits:**
  - Reduced financial risk
  - Flexibility to add units over time
  - Right size for replacement of retiring coal

GLOBAL DEVELOPMENT OF MATURE SMRs

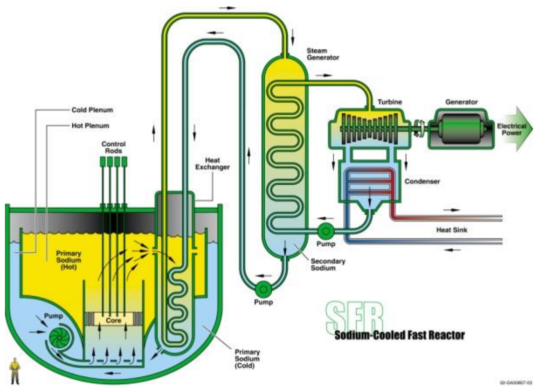
- **United States**
  - Integral PWRs (Holtec, NuScale, Westinghouse, mPower)
- **Republic of Korea**
  - SMART (90-100 MWe PWR)
- **China**
  - ACP100 (100 MWe PWR)
  - HTR-PM (High Temperature Gas-Cooled Reactor)
- **Argentina**
  - CAREM-25 (27 MWe PWR)
    - Plan to complete construction of a prototype in 2017
    - Would be used for electricity, desalination or as a research reactor
    - Full scale 200 MWe CAREM reactor to follow in early 2020’s
- **Russia**
  - Small Floating Nuclear Power Plants
    - Utilize two reactors derived from designs used in Russian nuclear icebreakers
    - Provide 70 MWe of power plus 586 GJ/hr heat

How a power plant based on the CAREM reactor could look (courtesy of Invap)

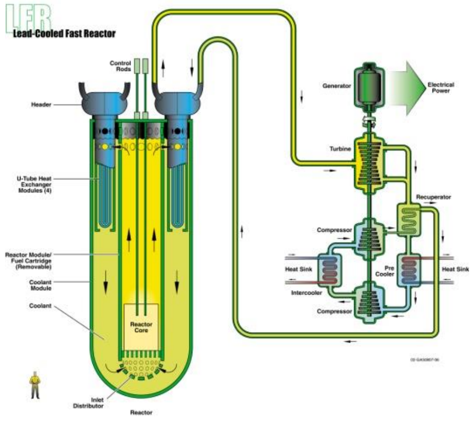
GENERATION IV REACTORS



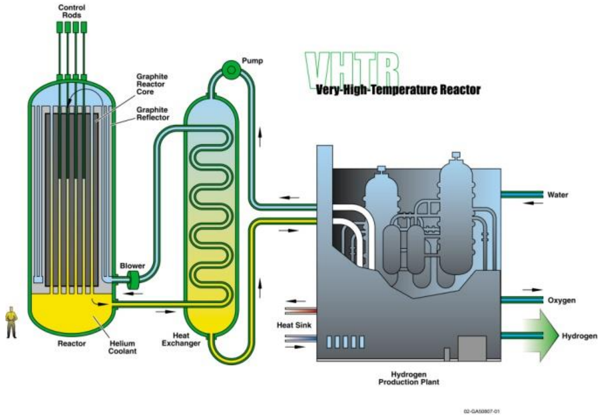
GENERATION IV REACTOR CONCEPTS



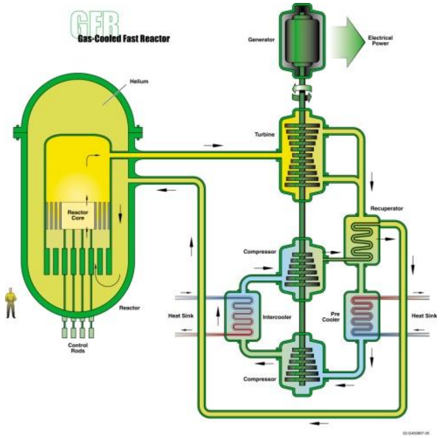
Sodium Fast Reactor



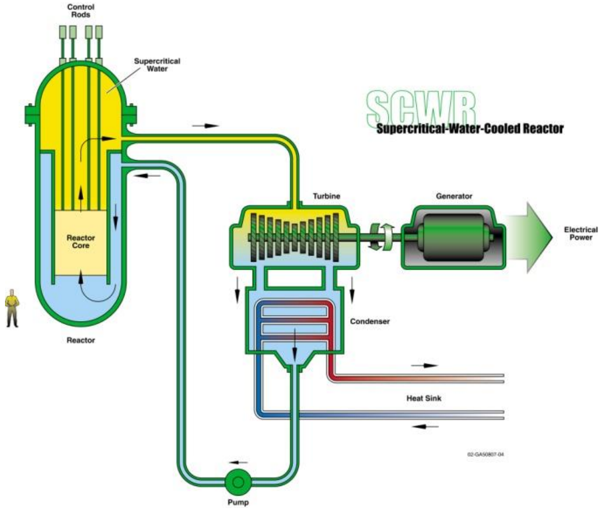
Lead Fast Reactor



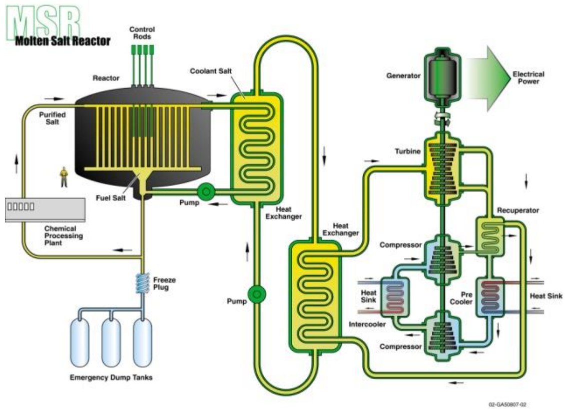
Very High Temperature Reactor



Gas-Cooled Fast Reactor



Super Critical Water Cooled Reactor



Molten Salt Cooled Reactor

GIF MEMBERS

- Argentina*
- Australia *
- Brazil *
- Canada
- China
- Euratom
- France
- Japan
- Korea, Rep. of
- Russian Federation
- South Africa
- Switzerland
- United Kingdom*
- United States

*Argentina, Australia, Brazil and the United Kingdom are non-active, i.e. they have not acceded to the Framework Agreement which establishes system and project organizational levels for further co-operation. Australia signed the GIF Charter on June 22, 2016, thus becoming the GIF's newest and 14th member.

ACTIVE R&D COLLABORATIONS

Generation IV Systems	Canada	China	France	Japan	Korea	Russia	Switzerland	U.S.A.	EU
Sodium-cooled Fast Reactor (SFR)		●	●	●	●	●		●	●
Very-high Temperature Gas cooled Reactor (VHTR)		●	●	●	●		●	●	●
Gas-cooled Fast Reactor (GFR)			●	●					●
Supercritical-water cooled Reactor (SCWR)	●	●		●		●			●
Lead-cooled Fast Reactor (LFR)				●	●	●			●
Molten Salt Reactor (MSR)			●			●	●		●

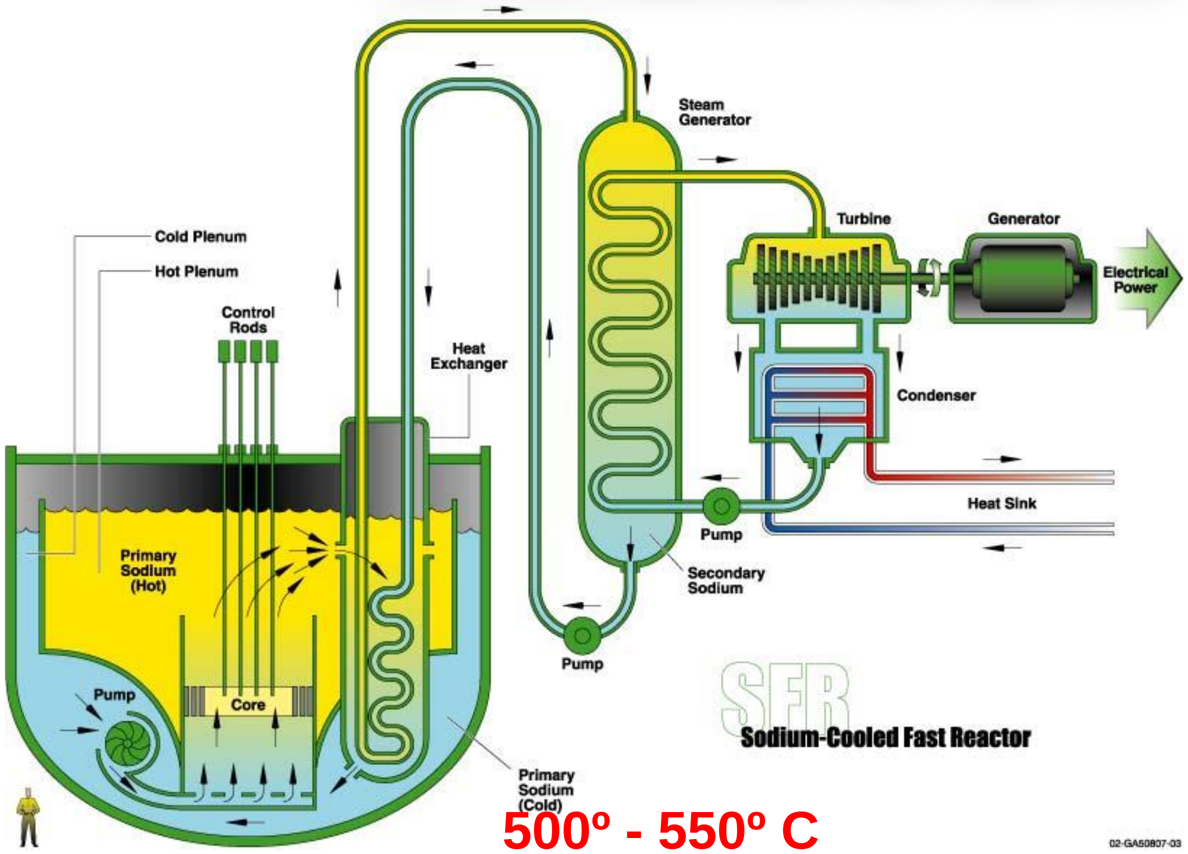
● *Participating member, signatory of a System Arrangement as of July 2016*

SODIUM FAST REACTOR

- Major Features
  - Fast neutron spectrum
  - Low pressure liquid metal coolant
  - Flexible fuel cycle applications

- More than 400 reactor years of operating experience since 1951
  - EBR-II, FFTF, Phenix, Superphenix, BOR-60, BN-600, and JOYO

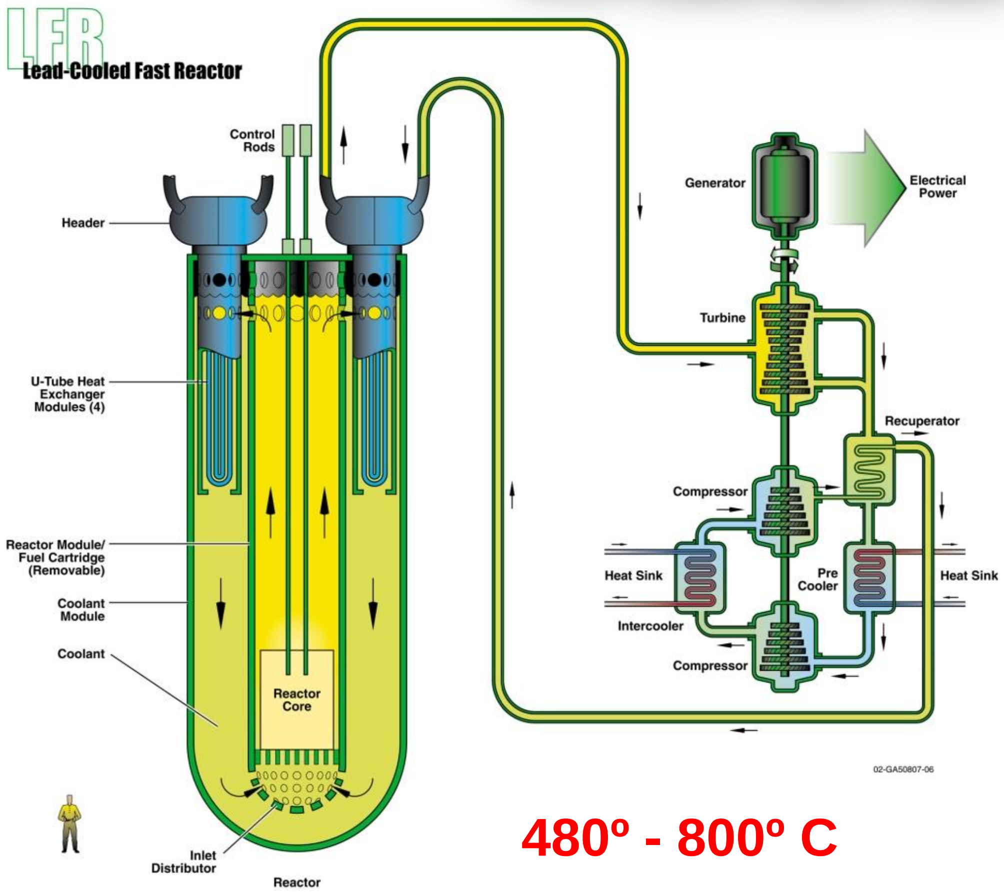
- All System Participants have SFR Design Activities



500º - 550º C

LEAD FAST REACTOR

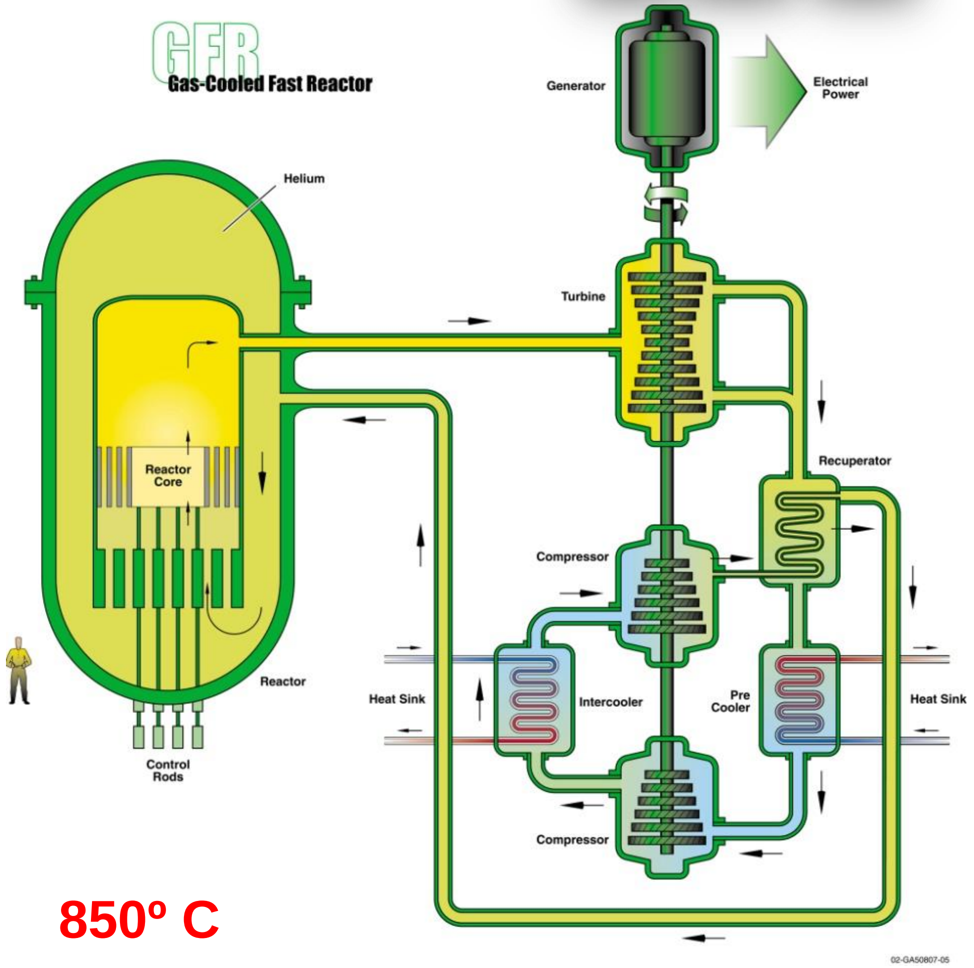
- Major Features
  - Liquid metal coolant that is not reactive with air or water
  - Lead or lead-bismuth eutectic options
  - Fast neutron spectrum
- Operating Experience
  - 80 reactor years of Russian submarine LBE reactor operation
- Most System Participants have LFR Design Activities in



480º - 800º C

GAS-COOLED FAST REACTOR

- Major Features
  - Fast neutron spectrum
  - Inert helium coolant
  - Very high temperature operation
  - Fuel cycle and non-electric applications
  - Significant development challenges for fuel, safety and components
- No operating experience for this challenging concept
- GFR Design Activities are Limited



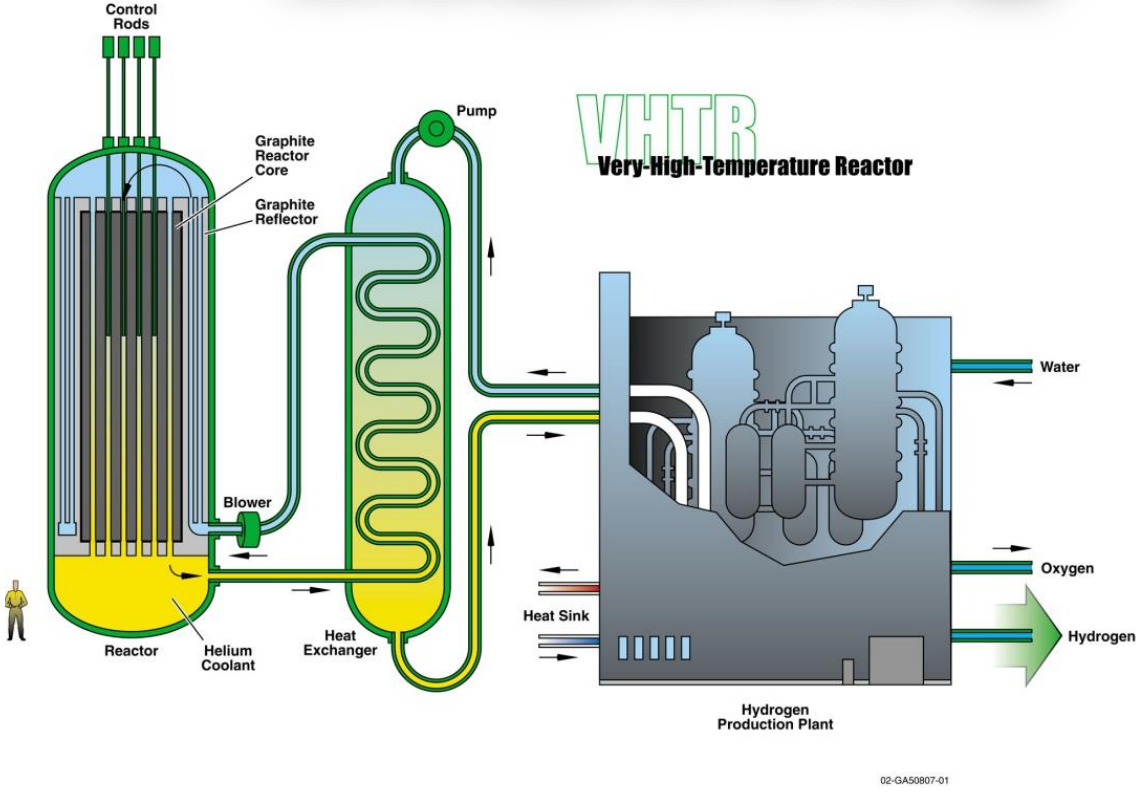
850º C

VERY HIGH TEMPERATURE REACTOR

- Major Features
  - Inert helium coolant
  - Unique TRISO fuel
  - Thermal neutron spectrum
  - Exceptional safety
  - Very high temperature operation
  - Non-electric applications

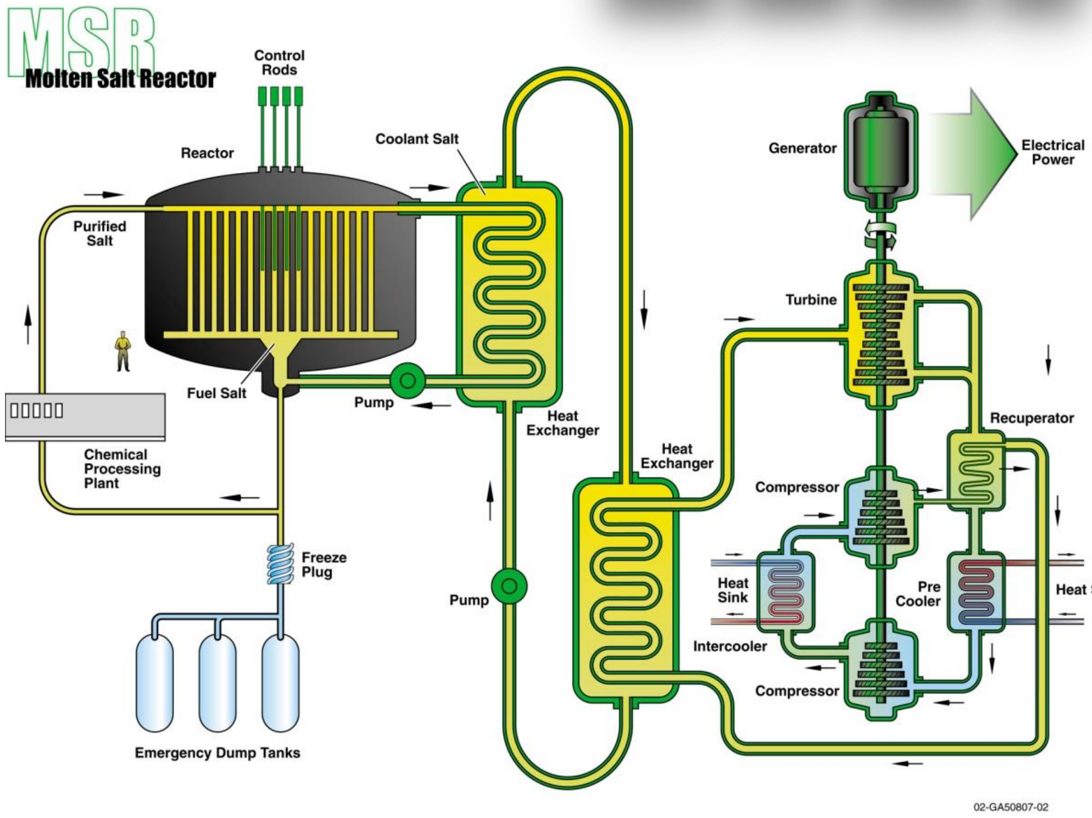
- Operating experience gained since 1963
  - AVR and THTR (Germany)
  - Peach Bottom and Fort St. Vrain (United States)
  - HTTR (Japan)
  - HT10 (China)

- Most System Participants have HTR Design Activities



MOLTEN SALT REACTOR

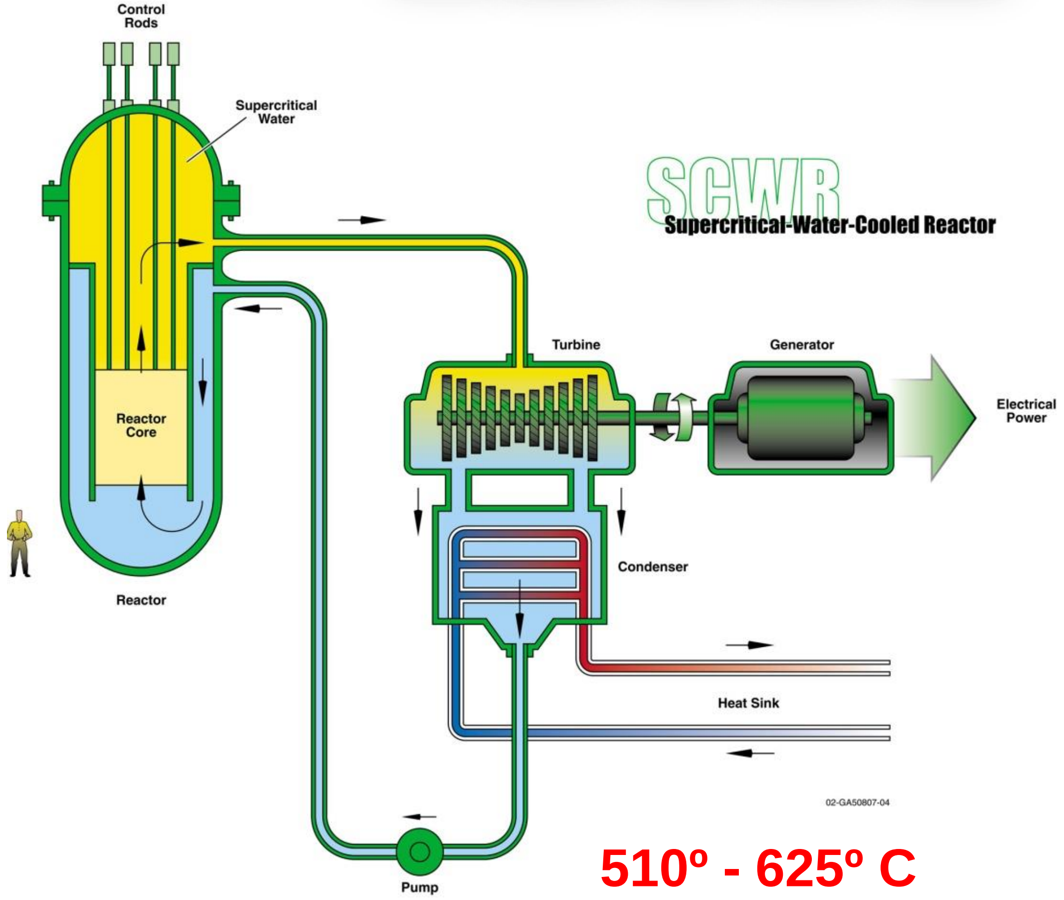
- Major Features
  - Molten salt eutectic coolant
  - High temperature operation
  - Thermal or fast spectrum
  - Molten or solid fuel
  - On-line waste Management
- Operating Experience
  - Molten Salt Reactor Experiment
  - Aircraft Reactor Experiment
- Most Participants have MSR Design Activities



700º - 800º C

SUPER CRITICAL WATER-COOLED REACTOR

- **Major Features**
  - Merges LWR or PHWR technology with advanced supercritical water technology used in coal plants
  - Operates above the thermodynamic critical point (374º C, 22.1 MPa) of water
  - Fast and thermal spectrum options
- **Operating Experience**
  - No SCWR has been constructed
  - Vast operating experience in supercritical coal plants
- **SCWR Design Activities**
  - First design effort in 1957
  - Pre-conceptual design by system participants



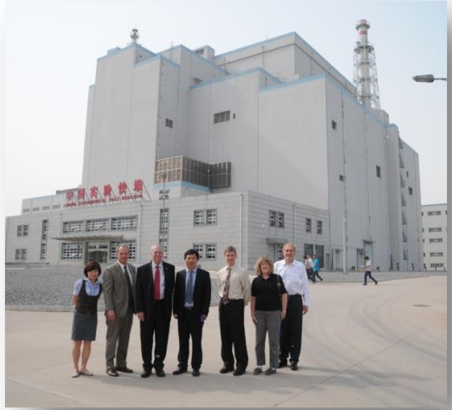
510º - 625º C

GEN IV REACTOR CONSTRUCTION IN CHINA

- Operation of Chinese Experimental Fast Reactor (20 MWe Test Reactor)
- Design of Chinese Prototype Fast Reactor
- Construction of demonstration High Temperature Gas Reactor
  - 200 MWe Pebble Bed design
  - Scheduled to start electricity generation by the end of 2017
- Design of a small Fluoride Salt Cooled Reactor

First Concrete poured for China's HTR-PM

CEFR construction



CEFR Finished

GENERATION IV REACTOR CONSTRUCTION IN RUSSIA

- Completion of BN-800 Reactor
  - Startup in 2016
- Design of BN-1200 Gen IV SFR
  - Competitive economics to LWRs.
- Design of MBIR test reactor to replace BOR-60
- Demonstration Project on Lead-Bismuth LFR

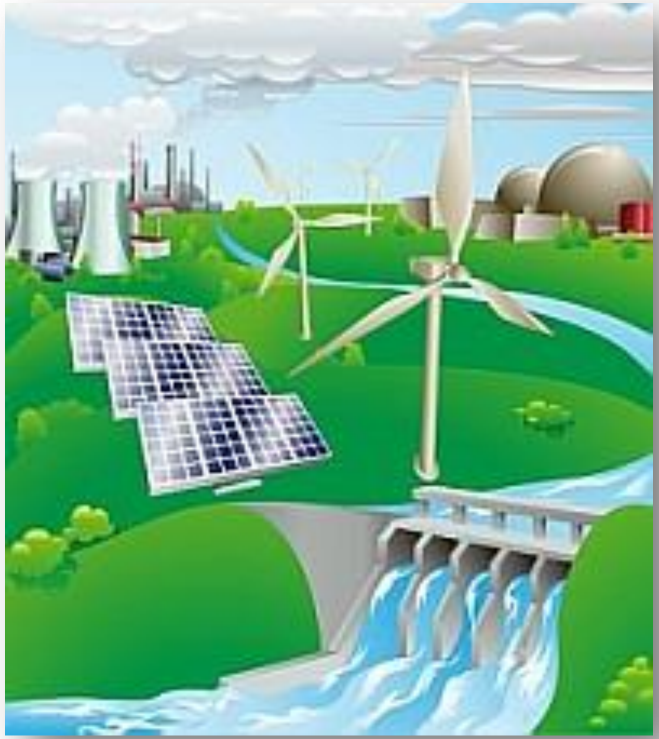
Reactor Compartment of Main Building

Steam Generator Compartment of Main Building

Turbine hall

SUMMARY

- First wave of reactors were driven by post-war economic growth in the industrialized world, concerns about energy supply/security, and strong government support.
- Today nuclear power is in its second wave and the worldwide interest is as strong as it was in 1953
- Reactors designs have evolved becoming safer, more reliable, and more economic
- Generation IV is progressing well and deployment is seen in the not too distant future



GEN IV International Forum[SM]

UPCOMING WEBINARS

19 October 2016	Closing the Fuel Cycle	Prof. Myung Seung Yang, Youngsan University
22 November 2016	Introduction to Nuclear Reactor Design	Dr. Claude Renault, CEA
15 December 2016	Sodium Cooled Fast Reactors	Dr. Robert Hill, ANL