The State-of-the-Art in Nuclear Power: Breeder Reactors and Beyond

American Association of Physics Teachers

Jacksonville, Florida

January 11, 2011

K. L. Peddicord, Director

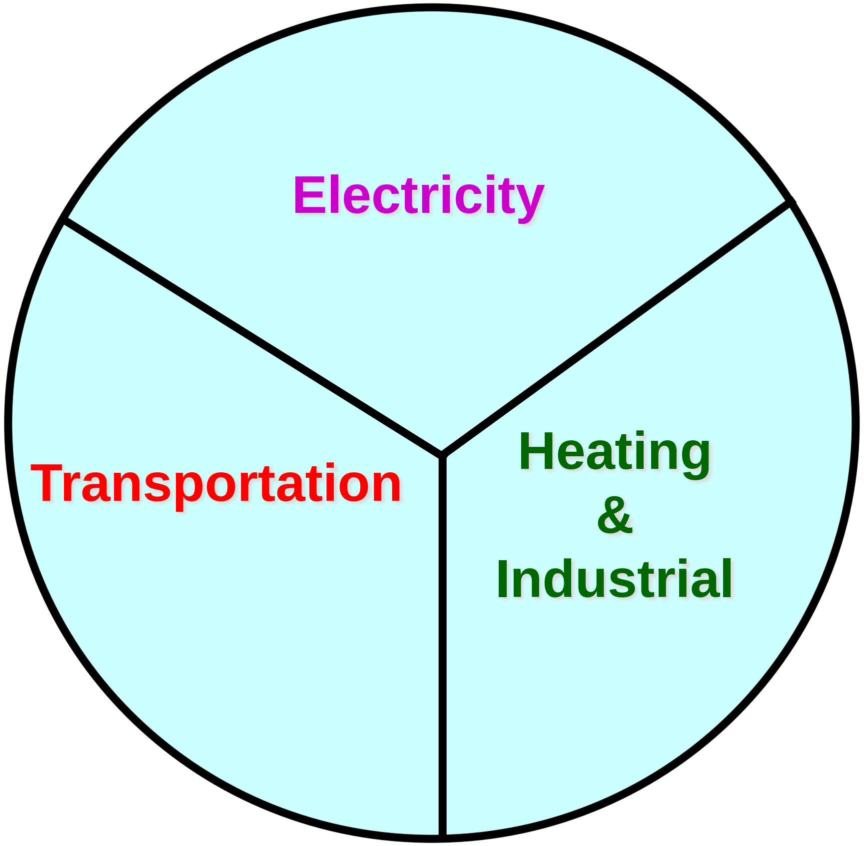
Nuclear Power Institute

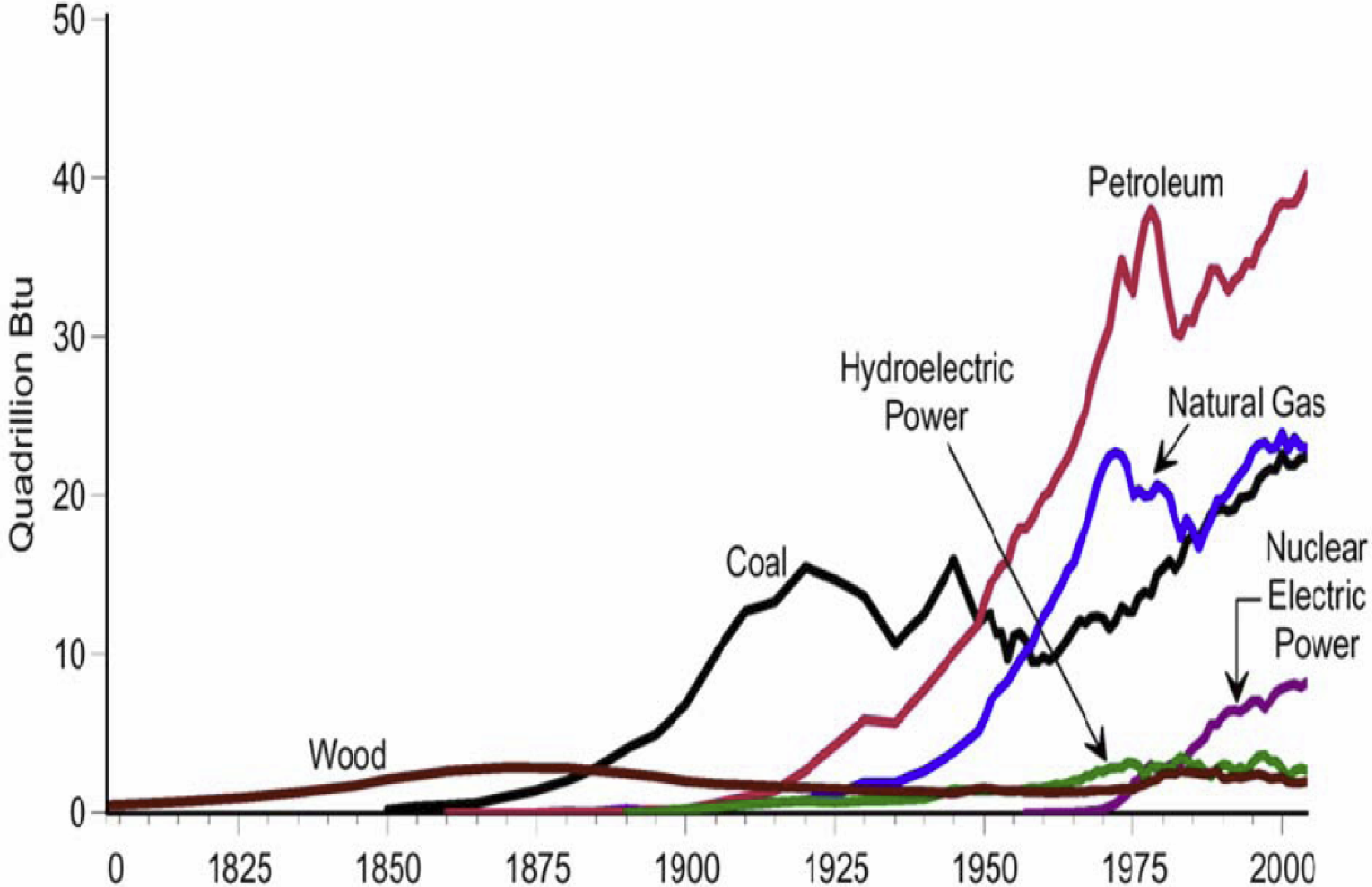
Professor of Nuclear Engineering

Texas A&M University

NUCLEAR POWER INSTITUTE
nuclearpowerinstitute.org

Uses of Primary Energy




Quadrillion Btu
50
40
30
20
10
0
0
1825
1850
1875
1900
1925
1950
1975
2000
Petroleum
Hydroelectric
Power
Natural Gas
Coal
Nuclear
Electric
Power
Wood

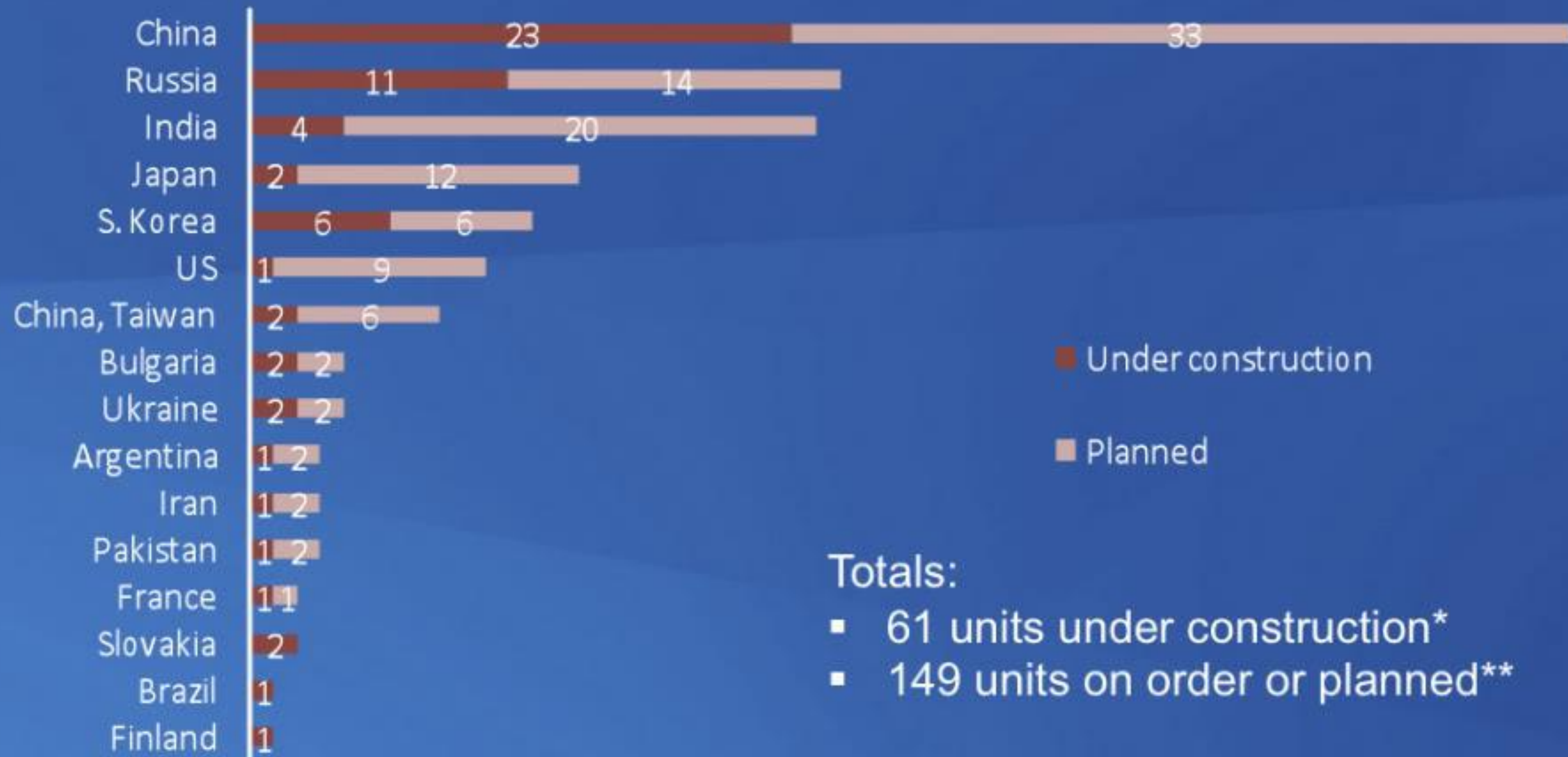
Today's Reactors

- Current world fleet totals 440 reactors
- Operating in 39 countries
- Generates approximately 20% of the global electricity, or 6% of the primary energy
- Most are light water reactors

Plans for New Reactors

- New construction underway of 61 reactors
- An additional 149 are planned
- In the U.S., 30 new plants have been announced to the Nuclear Regulatory Commission
- Two under construction in Georgia
- Globally some 53 new countries have announced their interest in nuclear to the International Atomic Energy Agency
- First will be built in the United Arab Emirates

Nuclear Units Under Construction and Planned Worldwide



Totals:

- 61 units under construction*
- 149 units on order or planned**

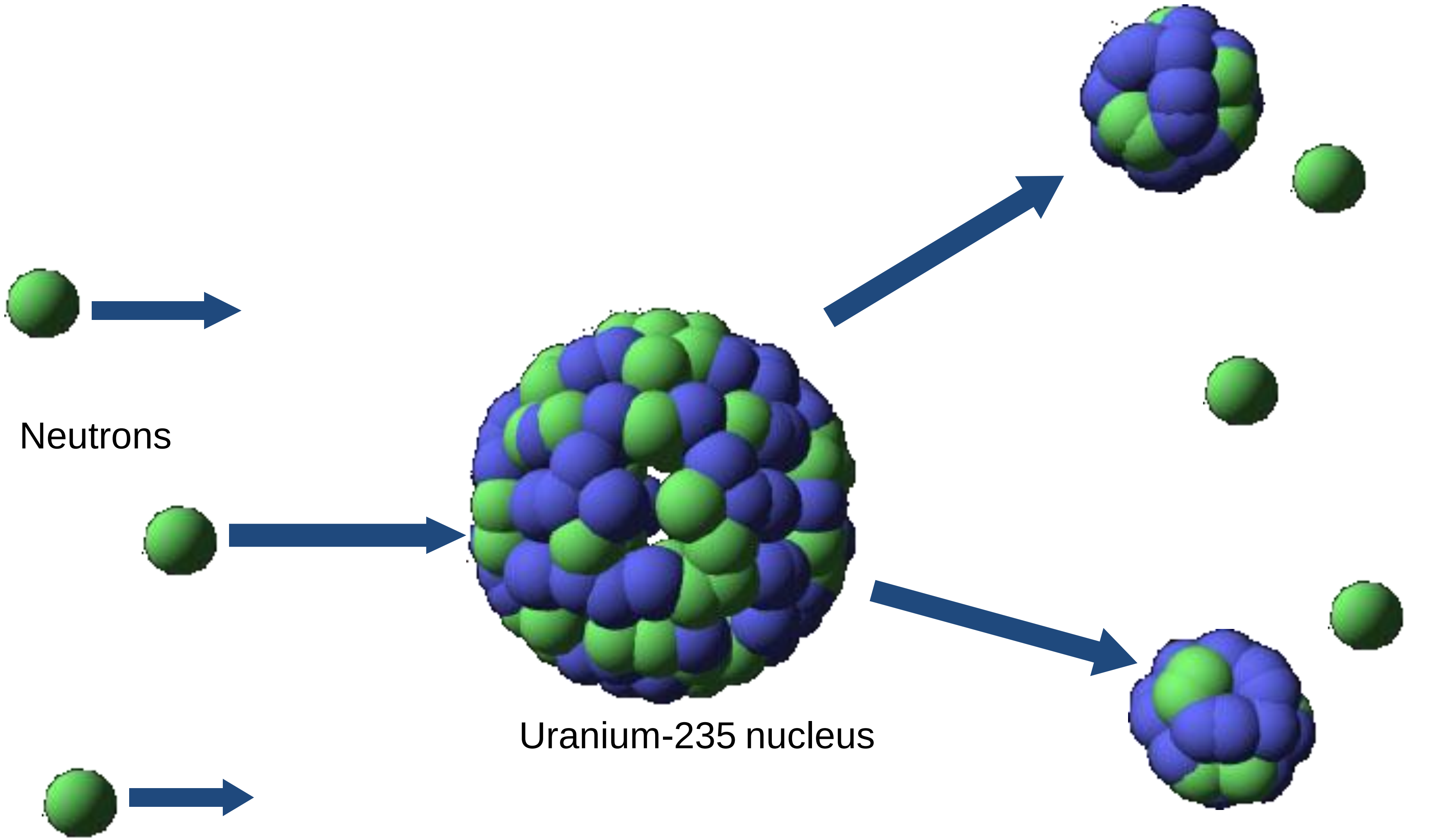
Sources: International Atomic Energy Agency for units under construction and World Nuclear Association for units on order or planned.

*Chart includes only countries with units under construction. **Countries planning new units are not all included in the chart.

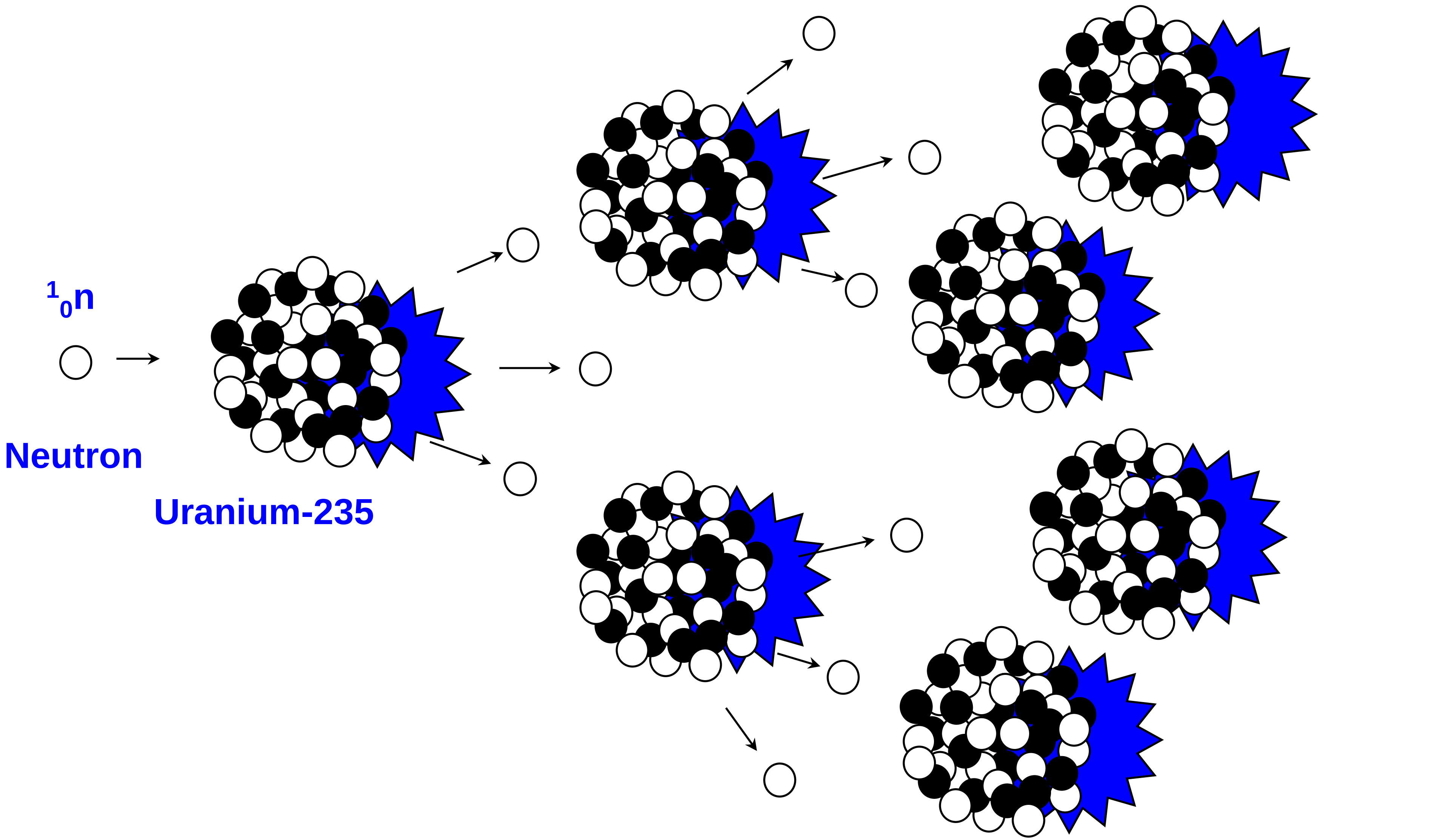
Planned units = Approvals, funding or major commitment in place, mostly expected in operation within 8-10 years.

Updated: 8/10

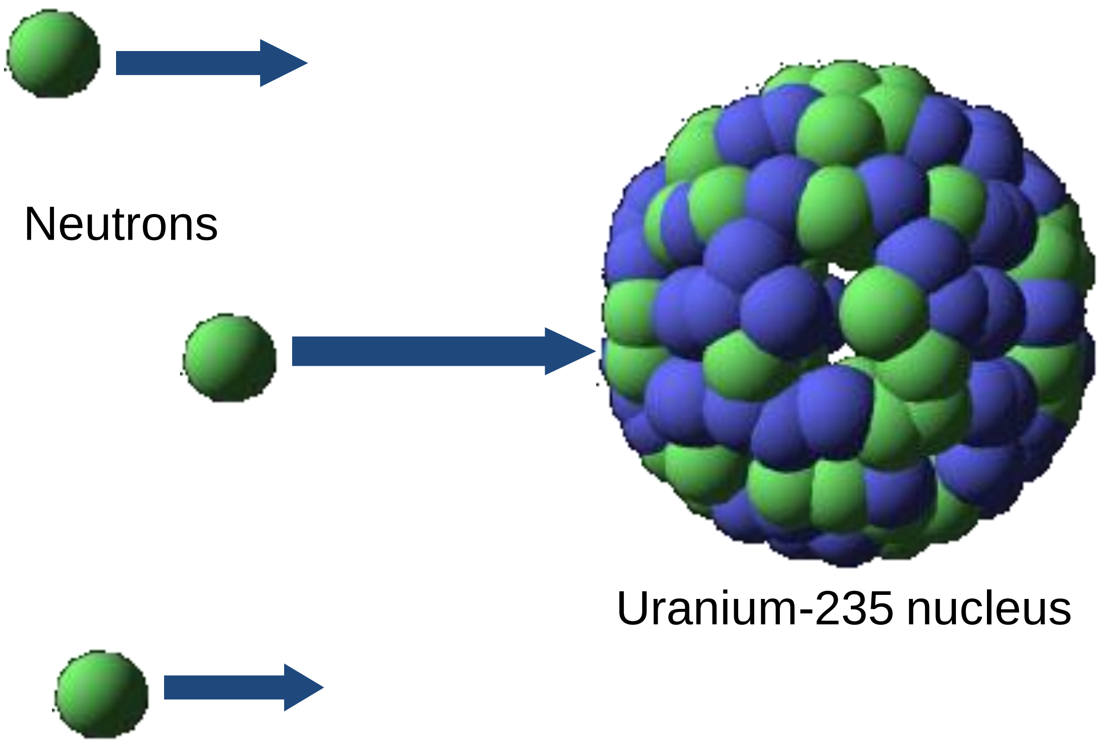
Nuclear Energy From Fission



The Neutrons Can Create a Fission Chain Reaction

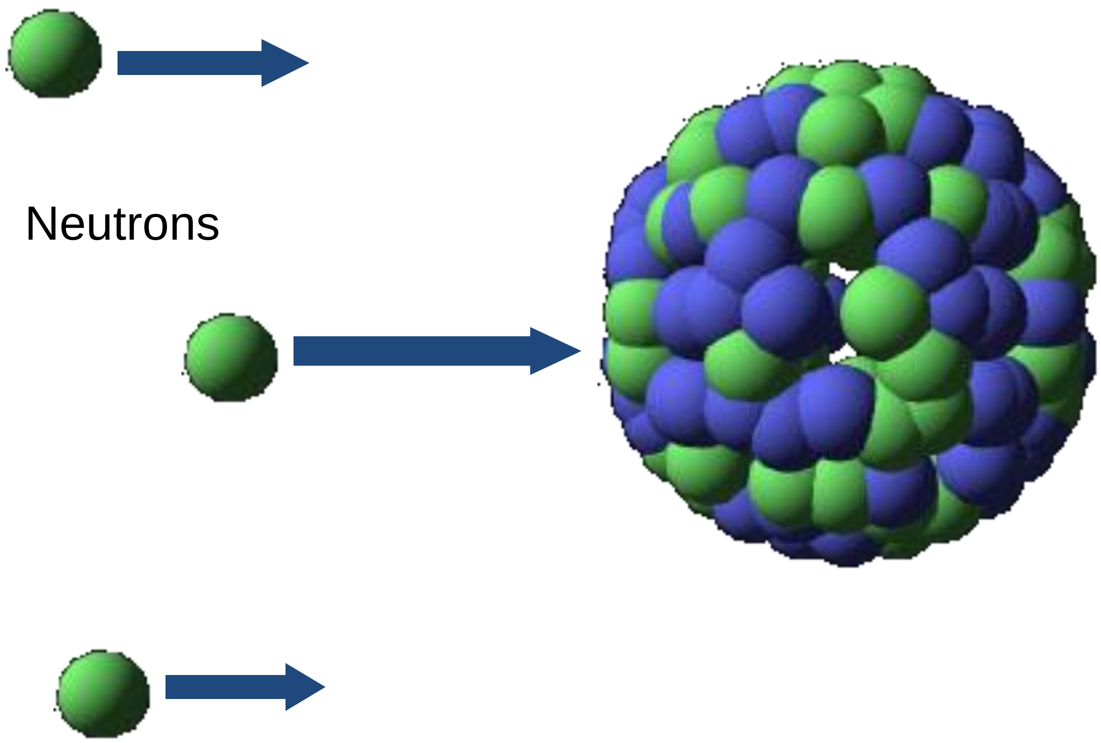


Important Parameters



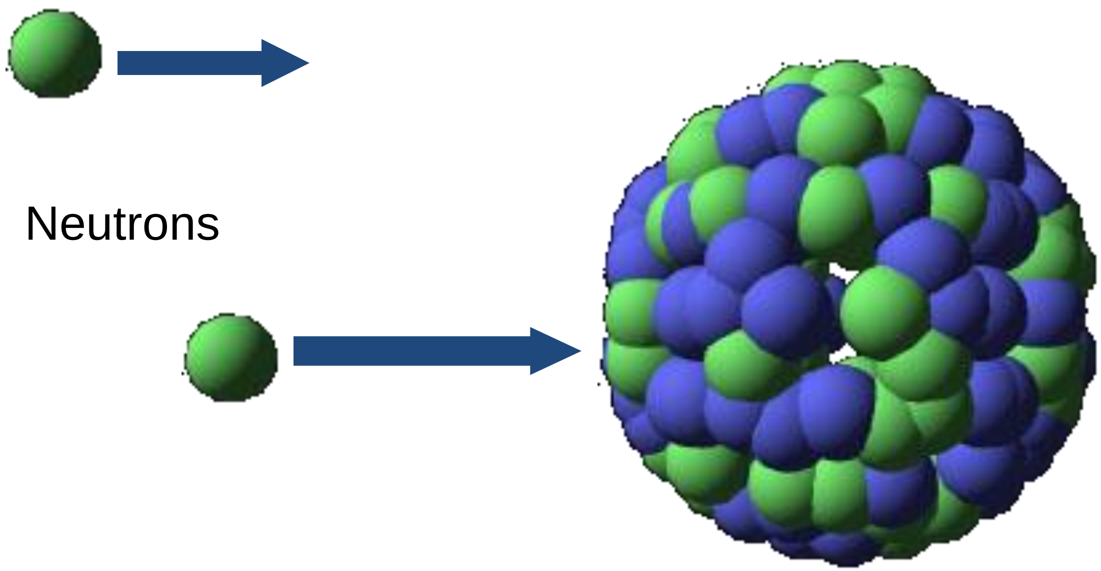
The "reference" fissile isotope is U-235. Occurs in nature. Plentiful. Approximately 0.74% of natural uranium is U-235. Remainder U-238.

Important Parameters (cont.)



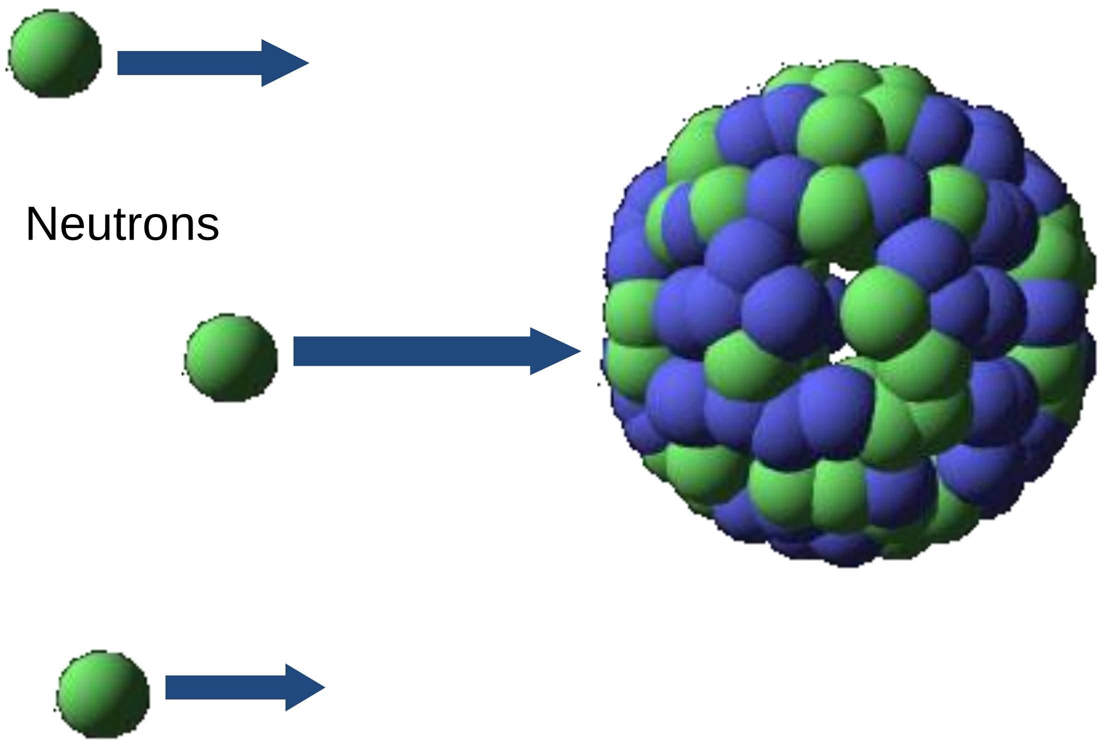
The “best” neutrons to be absorbed by U-235 are slow moving or “thermal” neutrons.

Important Parameters (cont.)

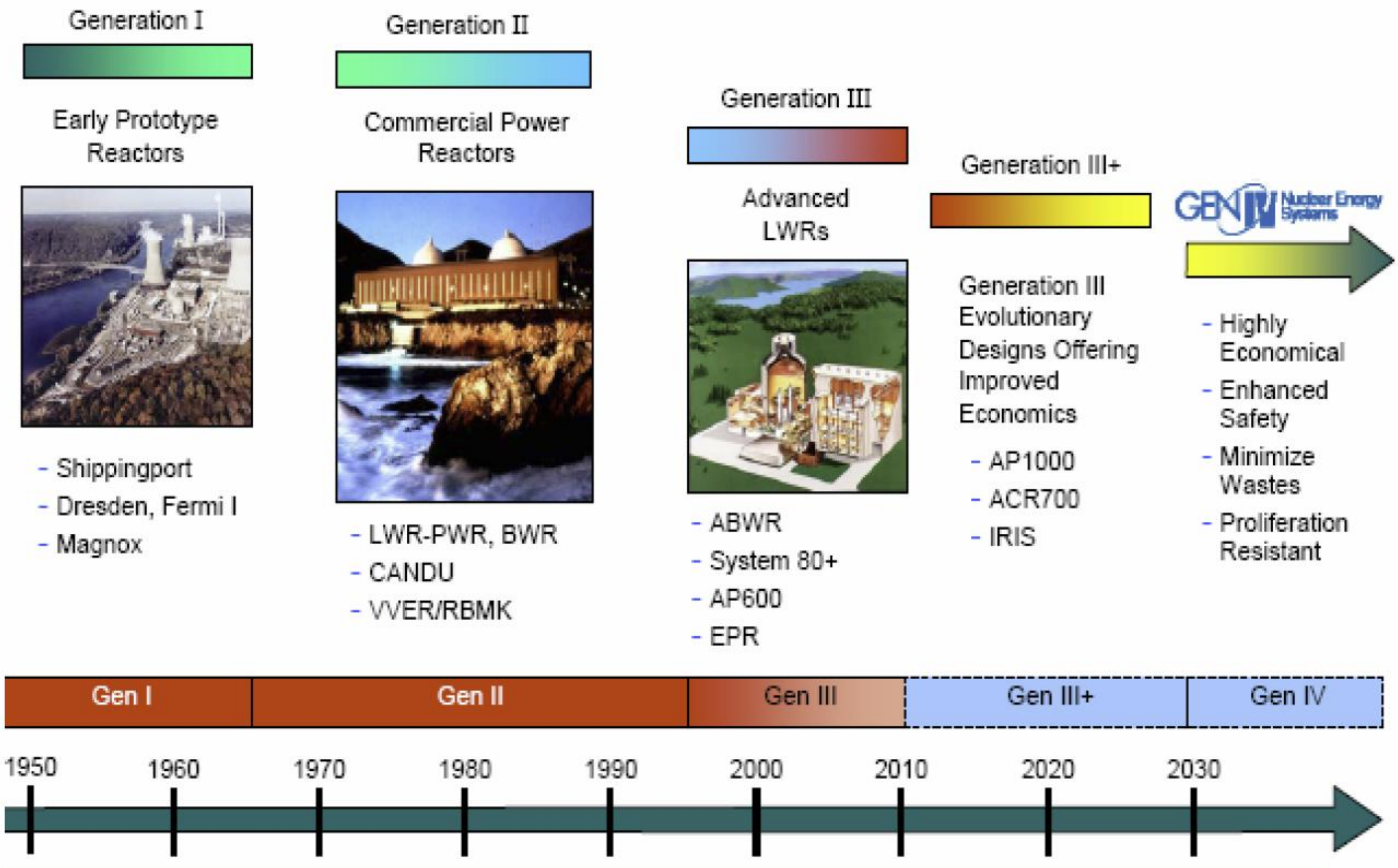


Approximately 84% of the thermal neutrons absorbed by a U-235 nucleus will cause fission. Each fission event releases about 2.43 new fast high energy neutrons, ~2 Mev.

Important Parameters (cont.)



For a light water reactor, the enrichment of the fuel must be increased to 3.5% to 5% U-235. The predominant fuel is UO_2.

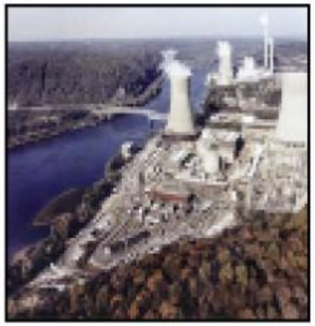

Generation I
Early Prototype Reactors
- Shippingport
- Dresden, Fermi I
- Magnox
Generation II
Commercial Power Reactors
- LWR-PWR, BWR
- CANDU
- VVER/RBMK
Generation III
Advanced LWRs
- ABWR
- System 80+
- AP600
- EPR
Generation III+
Generation III Evolutionary Designs Offering Improved Economics
- AP1000
- ACR700
- IRIS
GEN IV Nuclear Energy Systems
- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant
Gen I
Gen II
Gen III
Gen III+
Gen IV
1950
1960
1970
1980
1990
2000
2010
2020
2030

Generation-I
1950's and 60's

- Demonstrated nuclear power as central station generation of electricity
- Focused on light water and gas cooled designs
- Good performance
- Magnox plants in the United Kingdom operated for up to 50 years

Generation I

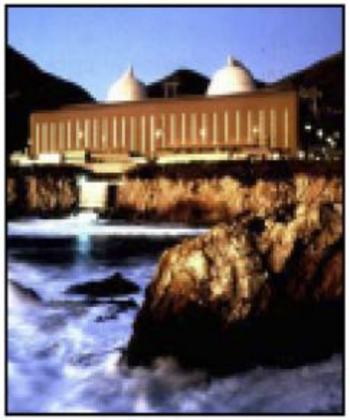
Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

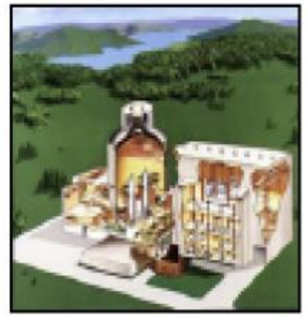
Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs



- ABWR
- System 80+
- AP600
- EPR

Generation III+

Generation III Evolutionary Designs Offering Improved Economics

- AP1000
- ACR700
- IRIS

GEN IV Nuclear Energy Systems

- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant

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

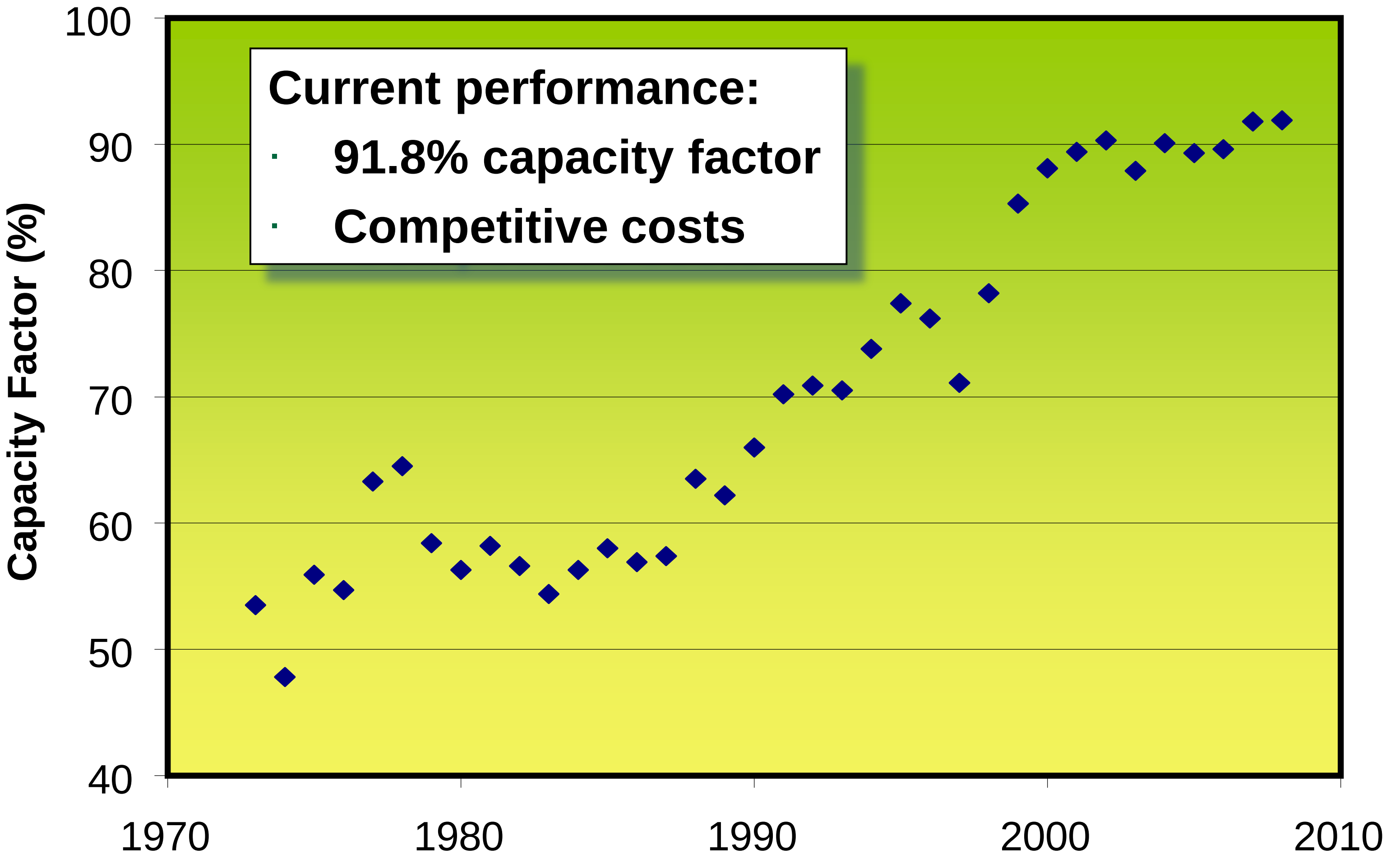
1950 1960 1970 1980 1990 2000 2010 2020 2030

Generation-II

- Designed in the 1960's and 1970's
- Each unit tended to be unique, contributing to increasing costs
- Little standardization, except for France
- Extensive design margins
- Improved analytical techniques had led power up-rates
- Outage management has resulted in higher capacity factors
- Achieved good, safe, economical performance

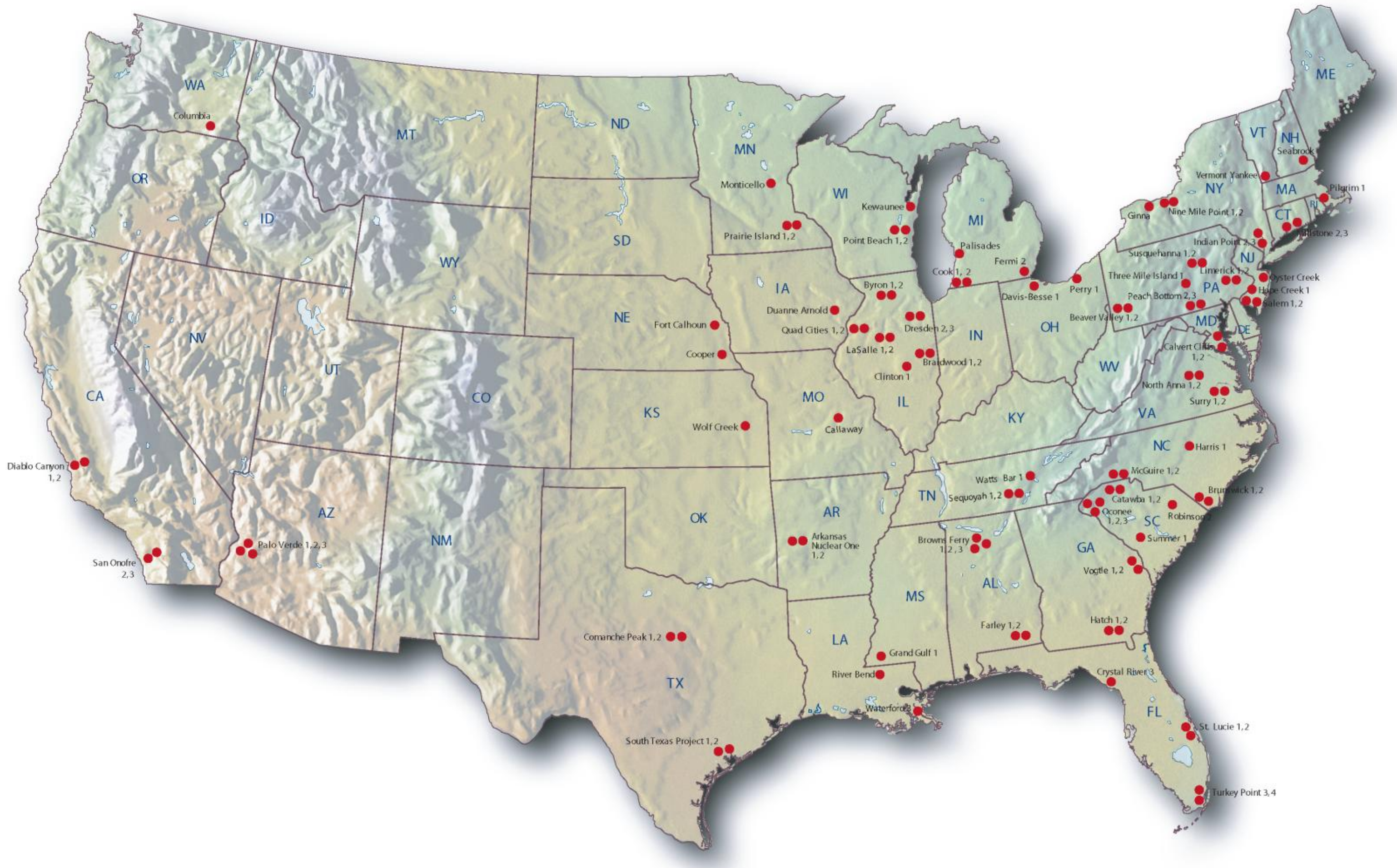
Generation II—Major Advances

Increased capacity factors and
power up-rates equivalent to 23 new 1000 MWe Plants



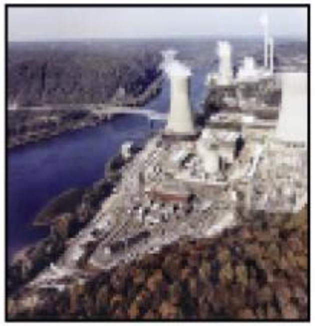
Source: Nuclear Energy Institute (2008)

U. S. NUCLEAR POWER PLANTS



Generation I

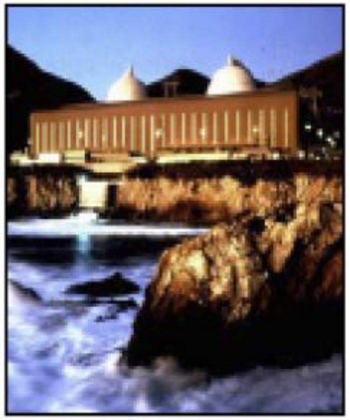
Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

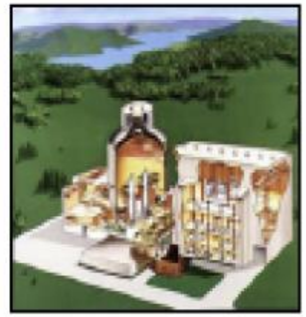
Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs



- ABWR
- System 80+
- AP600
- EPR

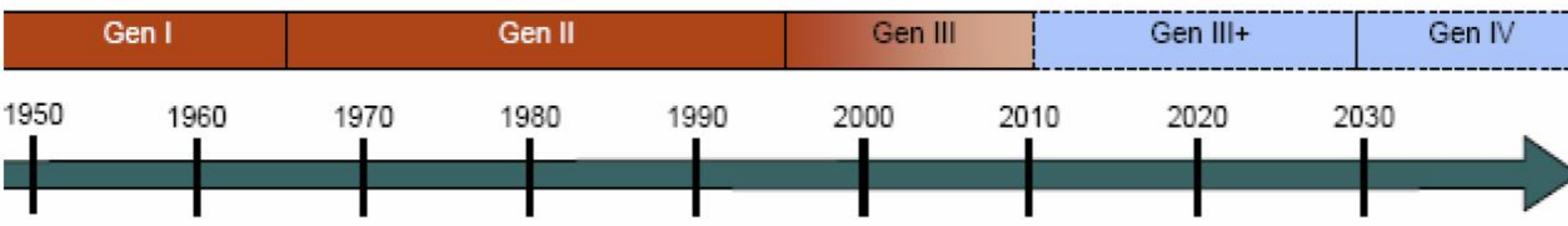
Generation III+

Generation III Evolutionary Designs Offering Improved Economics

- AP1000
- ACR700
- IRIS

GEN IV Nuclear Energy Systems

- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant



Generation-III and Generation-III$^+$

- Population and economic growth
- Pressure on fossil fuels
- Avoidance of CO_2 emissions
- Renewed interest in nuclear
- Foster new evolutionary designs
- Contributing to standardized, certified designs

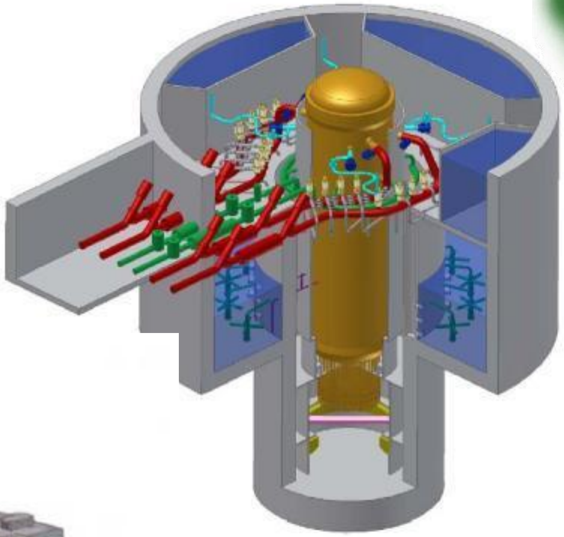
Gen-III and III$^+$ (continued)

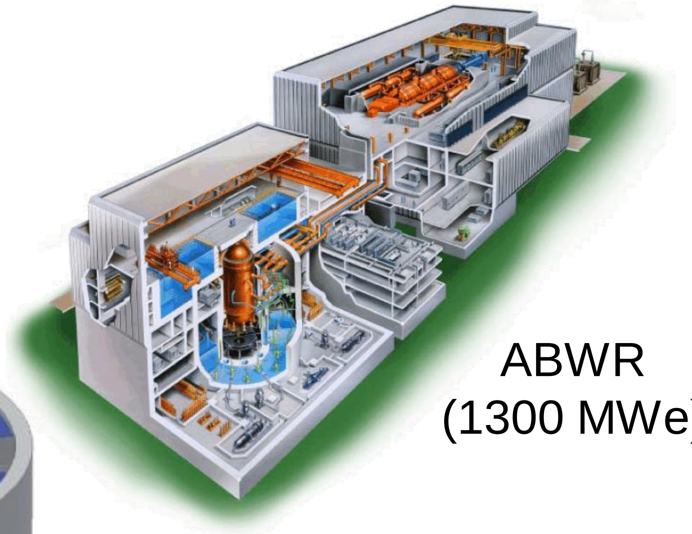
- Evolutionary changes, including passive safety features
- Simplified designs, reduction in the number of components, improve reliability
- Examples:
  - ABWR (Advanced Boiling Water Reactor)
  - EPR (European Pressurized Water Reactor)
  - AP-1000 (Advanced Pressurized Water Reactor)
  - ESBWR (Economic Simplified Boiling Water Reactor)

Generation-III and III+ Designs

AP-1000
(1140 MWe)

ESBWR
(1500 MWe)



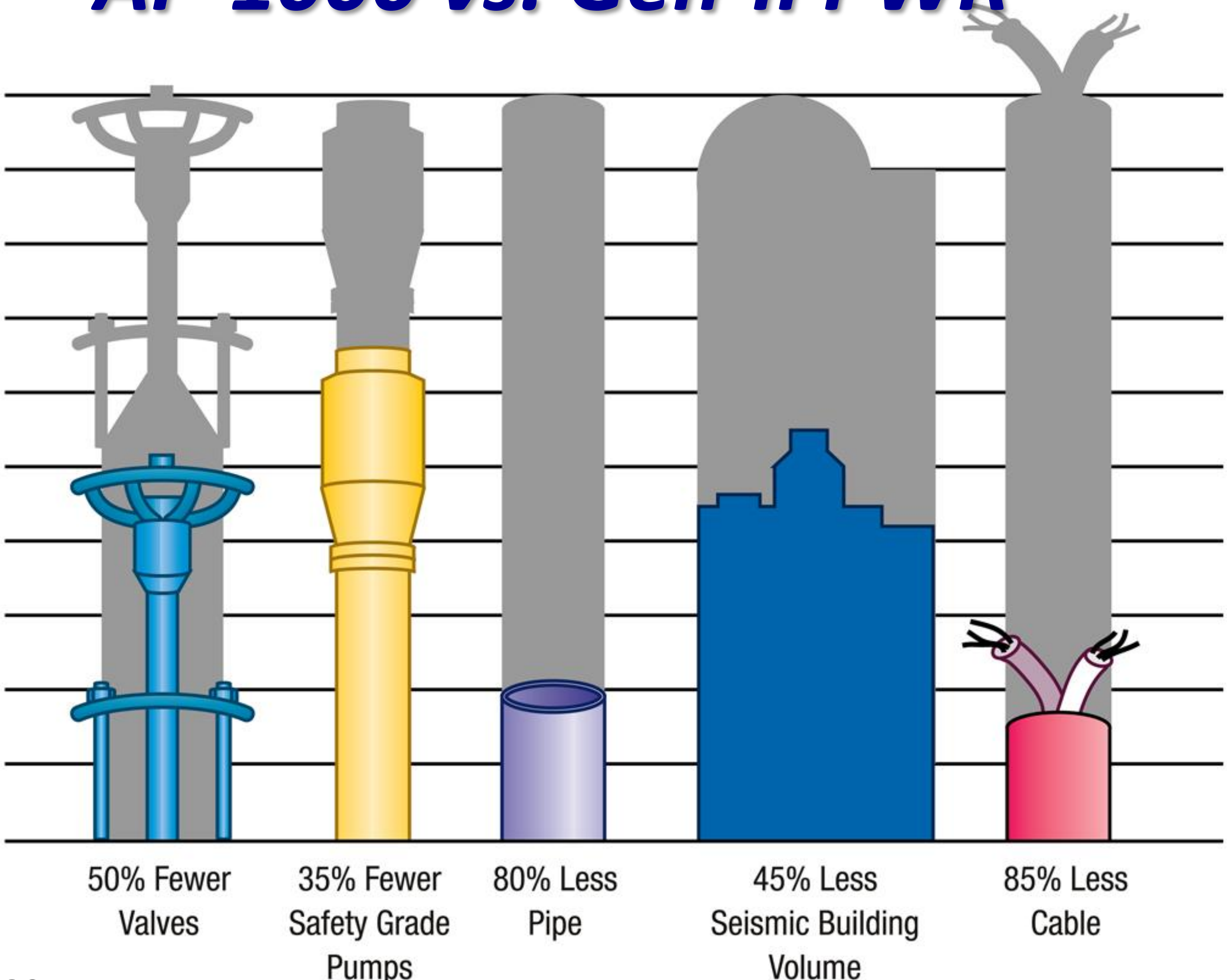


ABWR
(1300 MWe)

EPR
(1600 MWe)

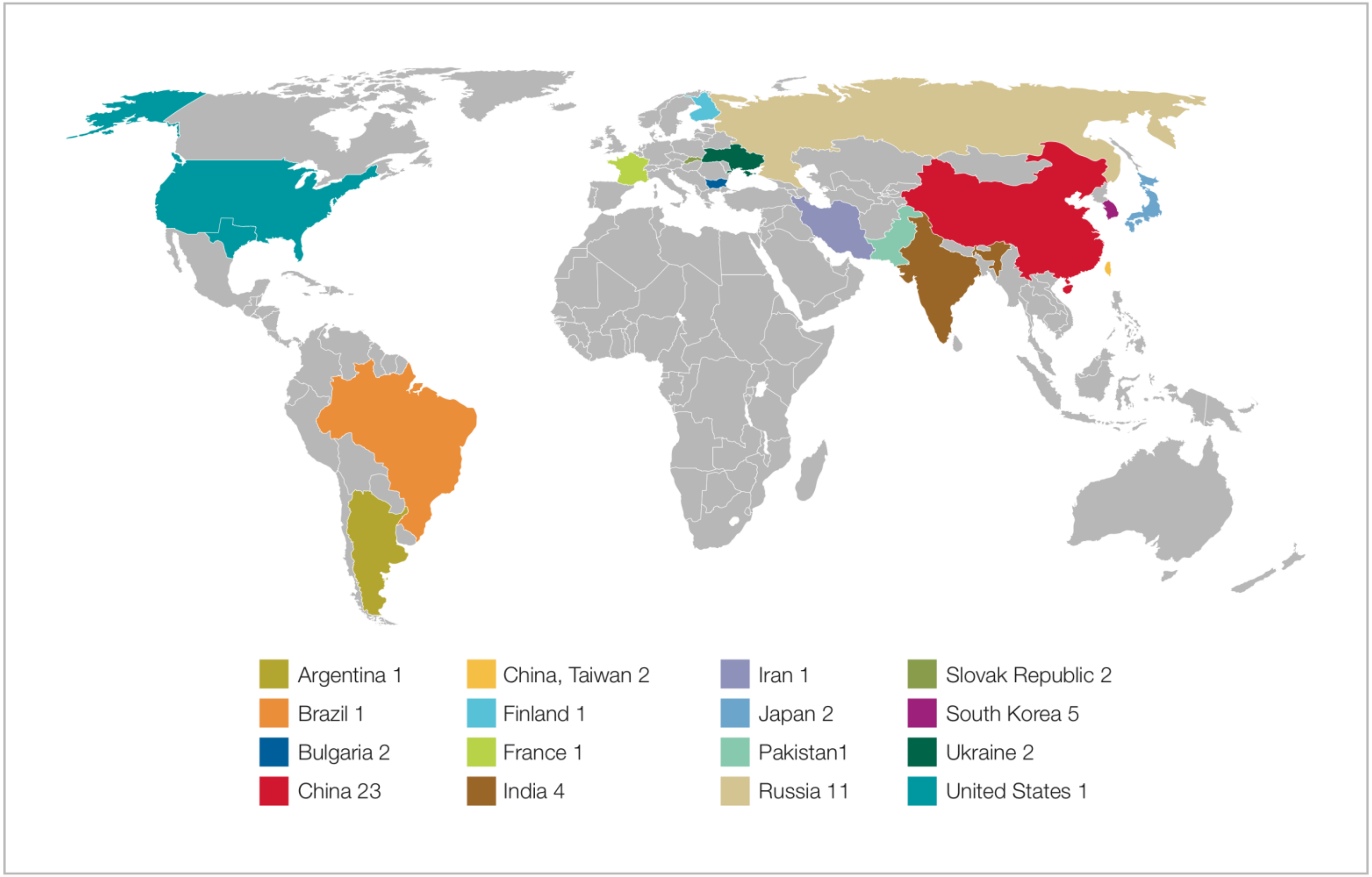
US APWR (1700 MWe)

AP-1000 vs. Gen-II PWR



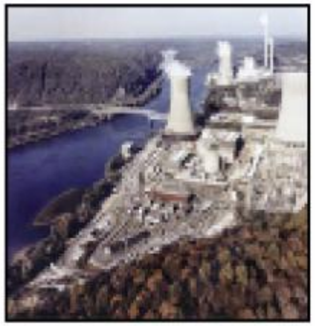
Westinghouse

New Construction



Generation I

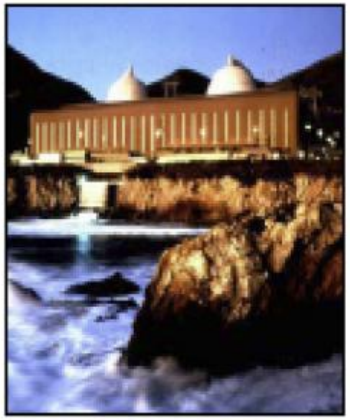
Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

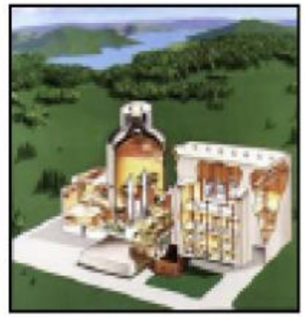
Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs



- ABWR
- System 80+
- AP600
- EPR

Generation III+

Generation III Evolutionary Designs Offering Improved Economics

- AP1000
- ACR700
- IRIS

GEN IV Nuclear Energy Systems

- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant

Gen I	Gen II	Gen III	Gen III+	Gen IV

1950 1960 1970 1980 1990 2000 2010 2020 2030

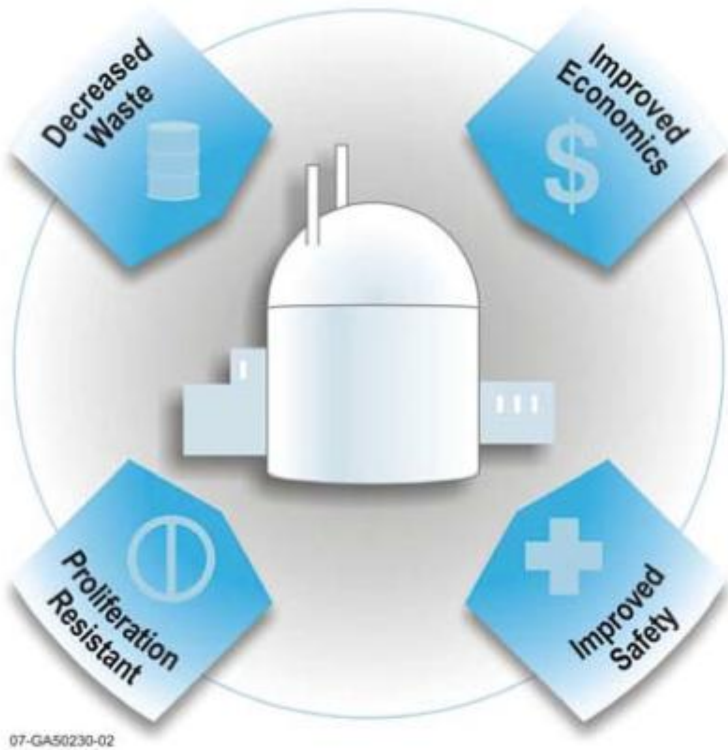
Generation-IV Systems

Goals for Generation IV Nuclear Energy Systems

Sustainability-1
Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

Sustainability-2
Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden thereby improving protection for the public health and the environment.

Proliferation Resistance and Physical Protection-1
Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials and provide increased physical protection against acts of terrorism.



Economics-1
Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

Economics-2
Generation IV nuclear energy systems will have a level of financial risks comparable to other energy projects.

Safety and Reliability -1
Generation IV nuclear energy systems operations will excel in safety and reliability.

Safety and Reliability-2
Generation IV nuclear energy systems will have a very low likelihood and degree of reactor damage.

Safety and Reliability -3
Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

Generation-IV Systems

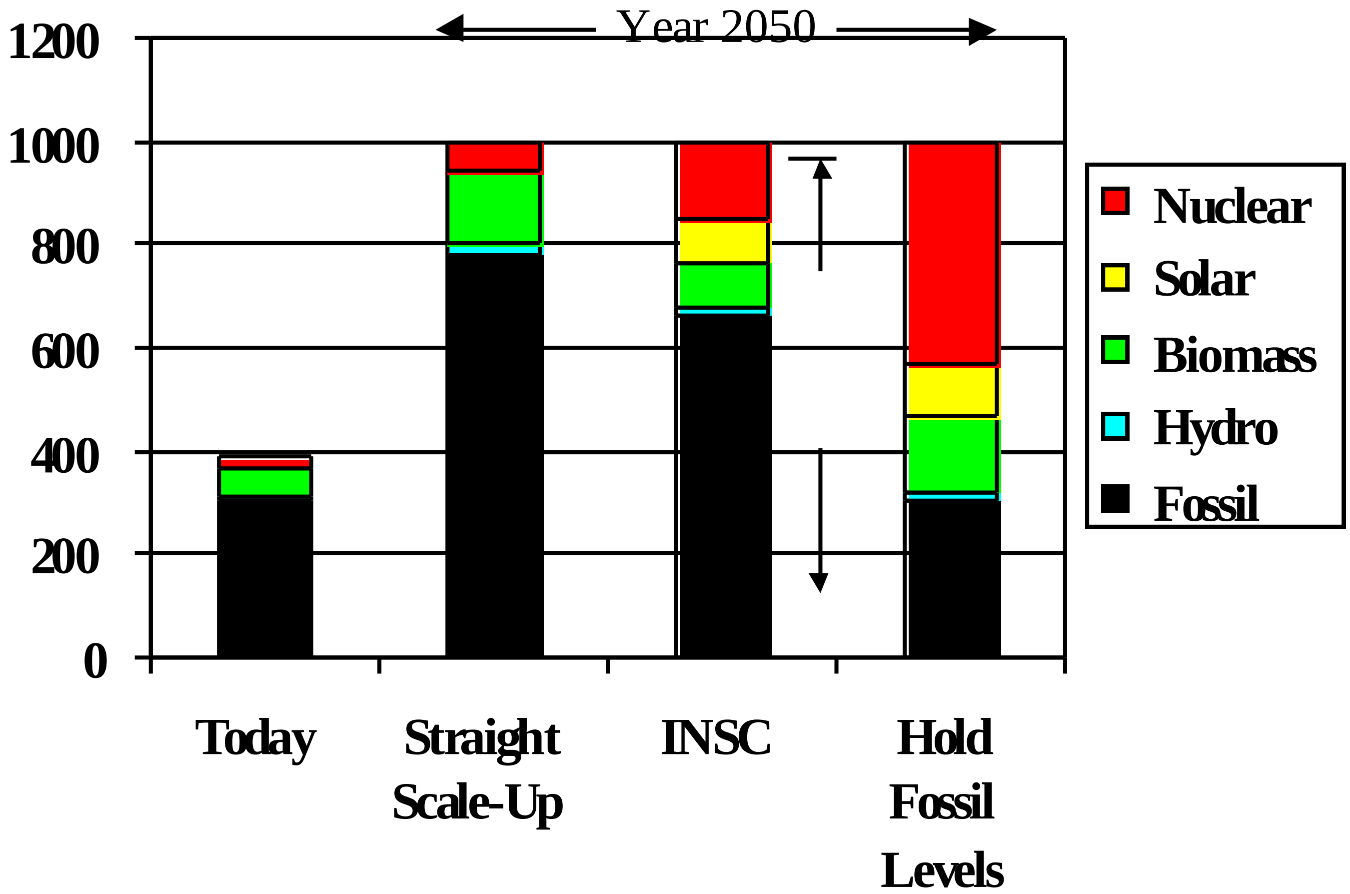
- **Very-High-Temperature Reactor (VHTR)**: a graphite-moderated, helium-cooled reactor, once-through uranium fuel cycle
- **Supercritical-Water-Cooled Reactor (SCWR)**: high-temperature, high-pressure water-cooled design, operates above the critical point of water
- **Gas-Cooled Fast Reactor (GFR)**: features a fast-neutron-spectrum, helium-cooled reactor and closed fuel cycle
- **Sodium-Cooled Fast Reactor (SFR)**: sodium coolant, closed fuel cycle, efficient management of actinides and conversion of fertile uranium
- **Lead-Cooled Fast Reactor (LFR)**: fast-spectrum lead or lead/bismuth eutectic coolant, closed fuel cycle, very efficient conversion of uranium and actinides
- **Molten Salt Reactor (MSR)**: circulating molten salt fuel mixture, epithermal-spectrum reactor, full actinide recycle fuel cycle

World Energy Perspective

Projected growth over the next half century
(International Nuclear Societies Council)

Year	Population (Billions)	GJ/Person	Total Energy (EJ)
2000	6	67	400
2050	10	100*	1000

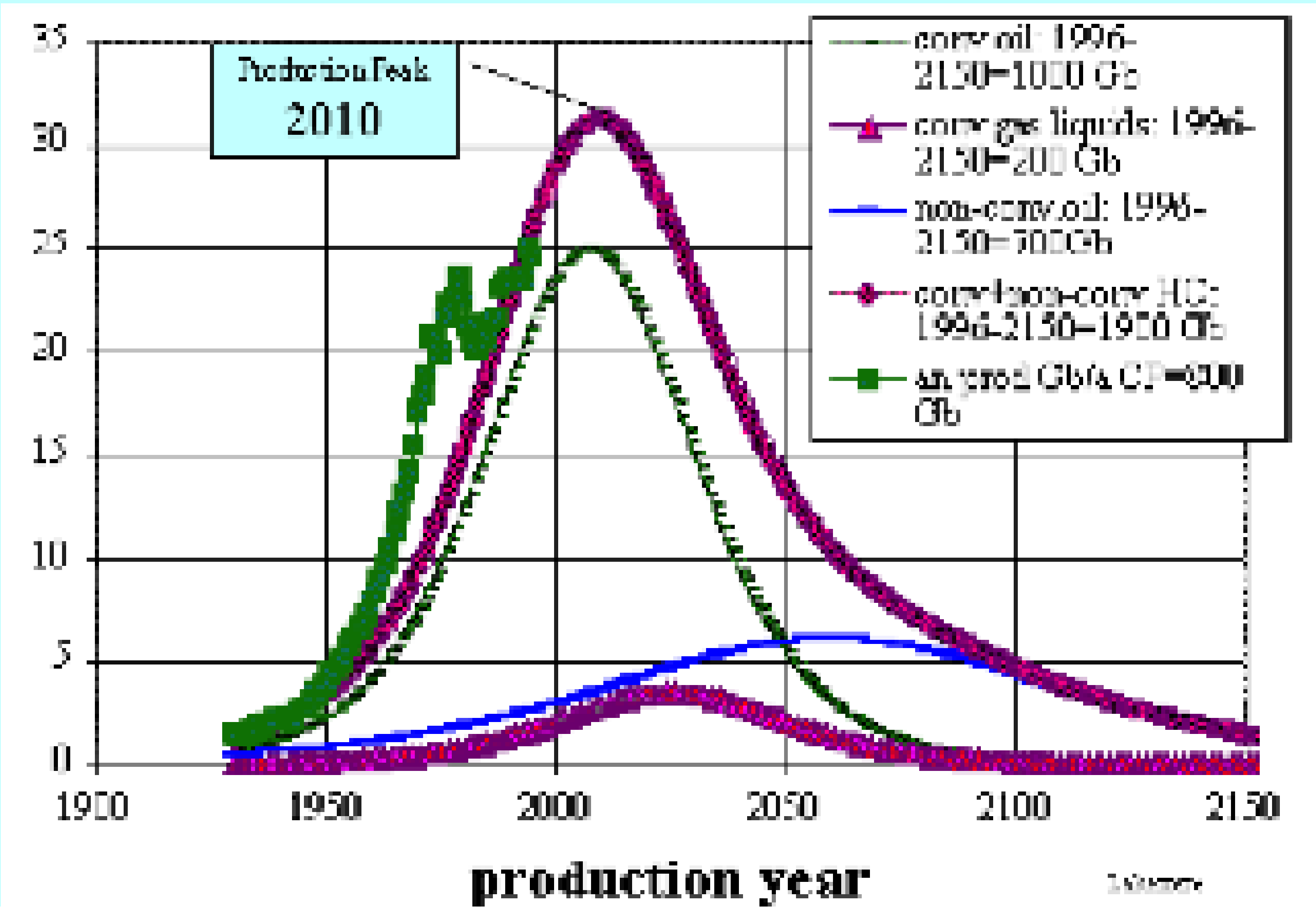
* NOTE: U.S. Today ~ 300 GJ/Person
100 GJ/Person represents 5 times increase for poor nations



Year 2050
1200
1000
800
600
400
200
0
Today
Straight Scale-Up
INSC
Hold Fossil Levels
Nuclear
Solar
Biomass
Hydro
Fossil

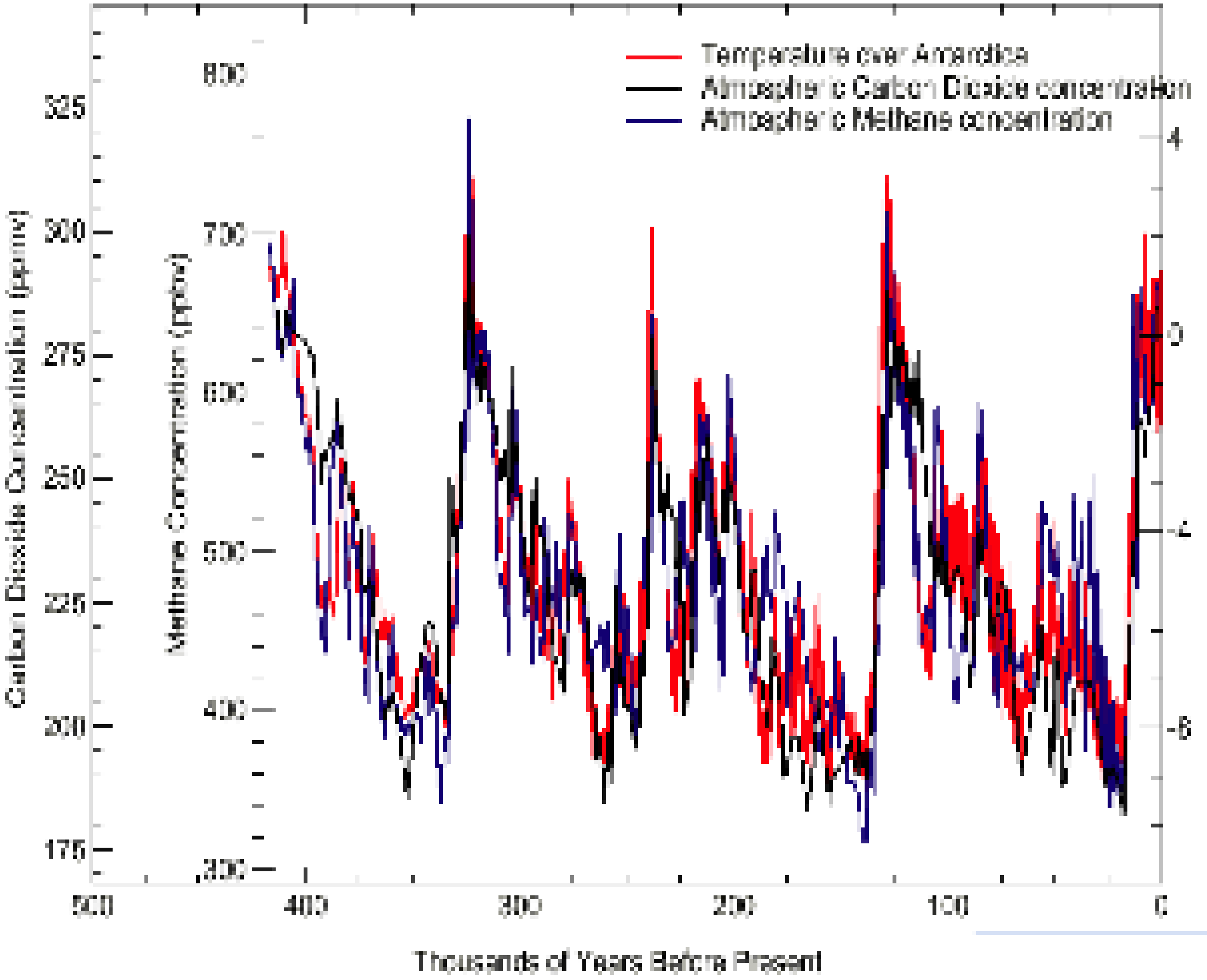
Laherrere's Oil Production Forecast, 1930-2150

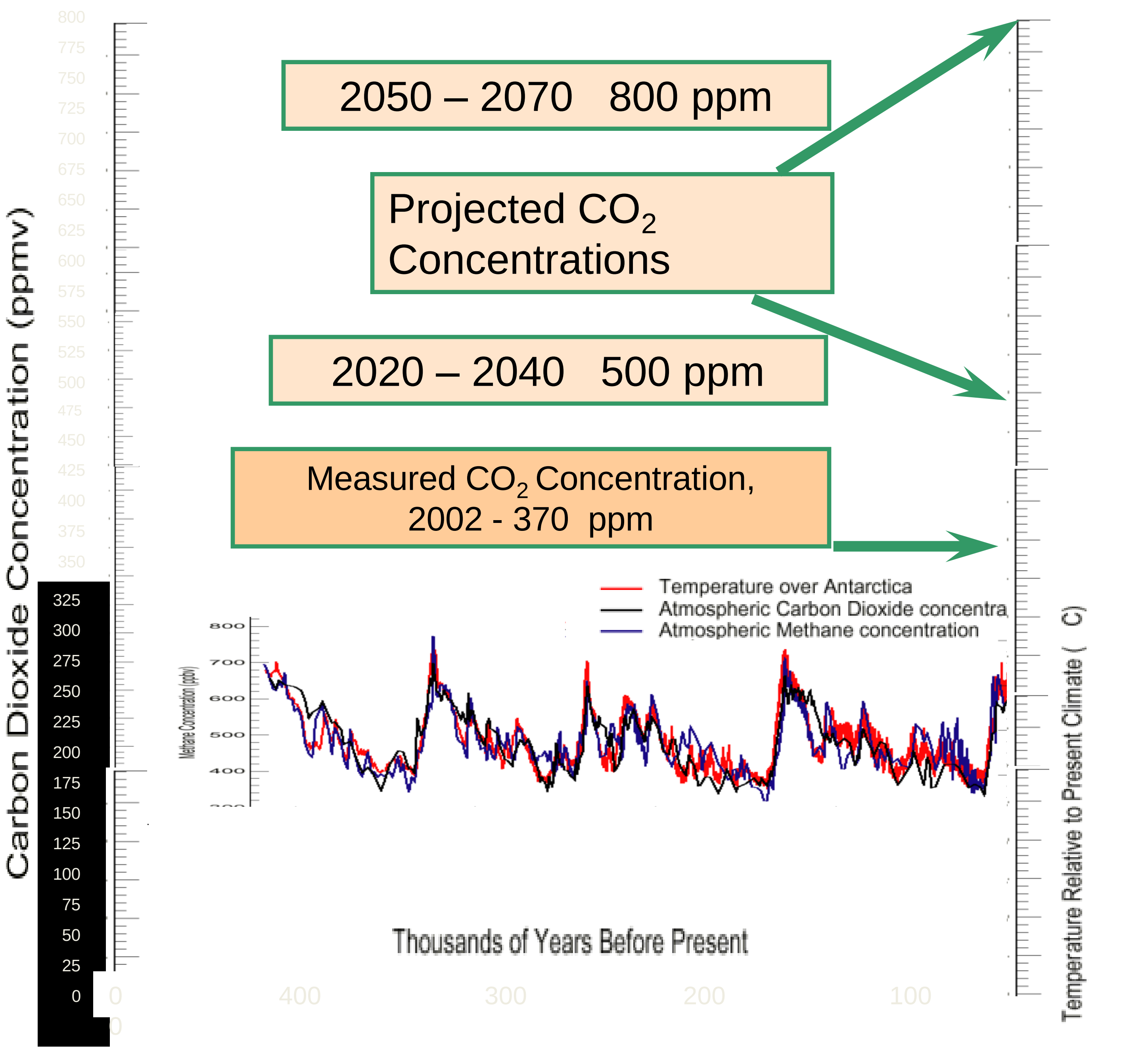
Energy Availability



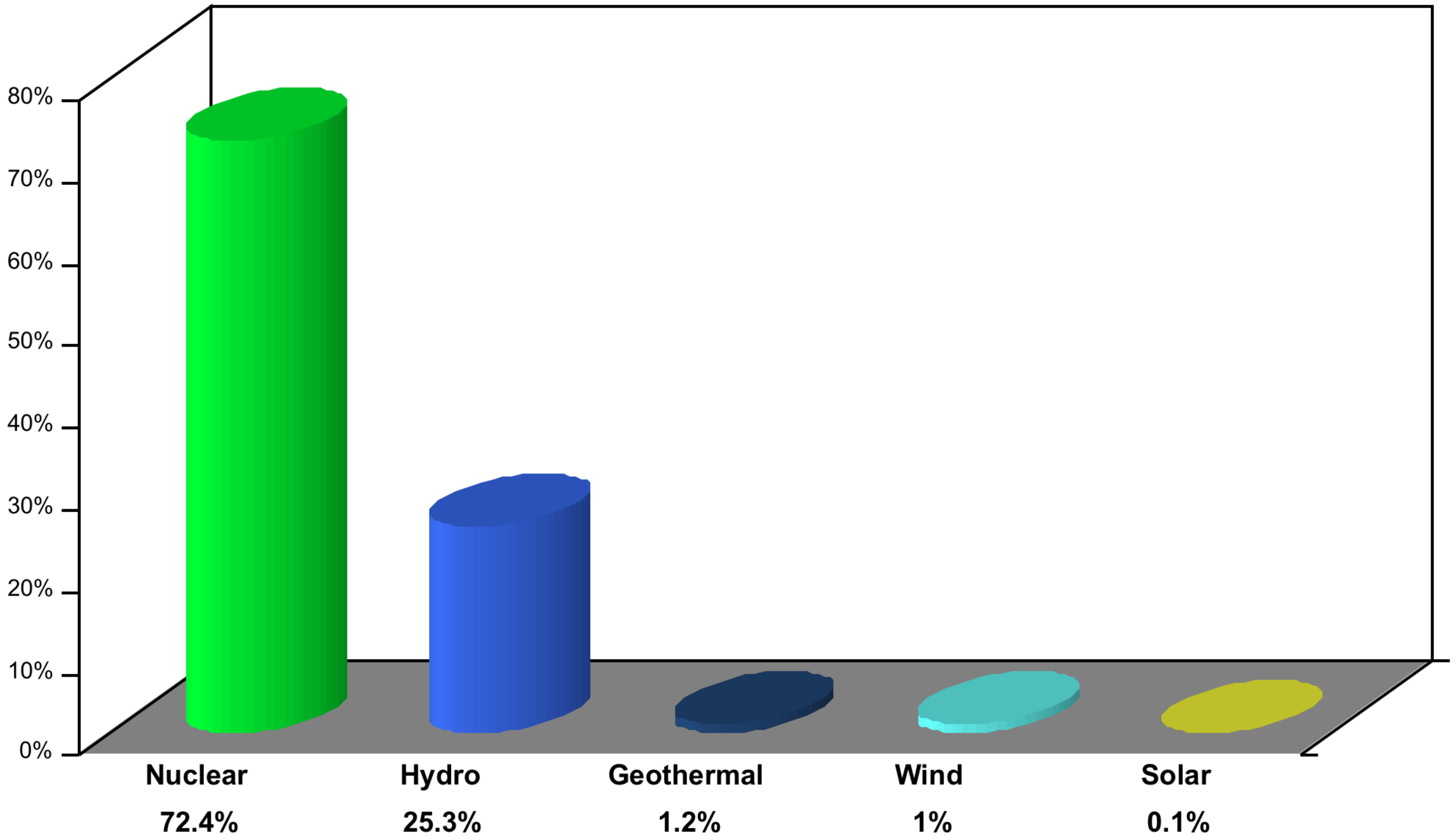
Environmental Considerations

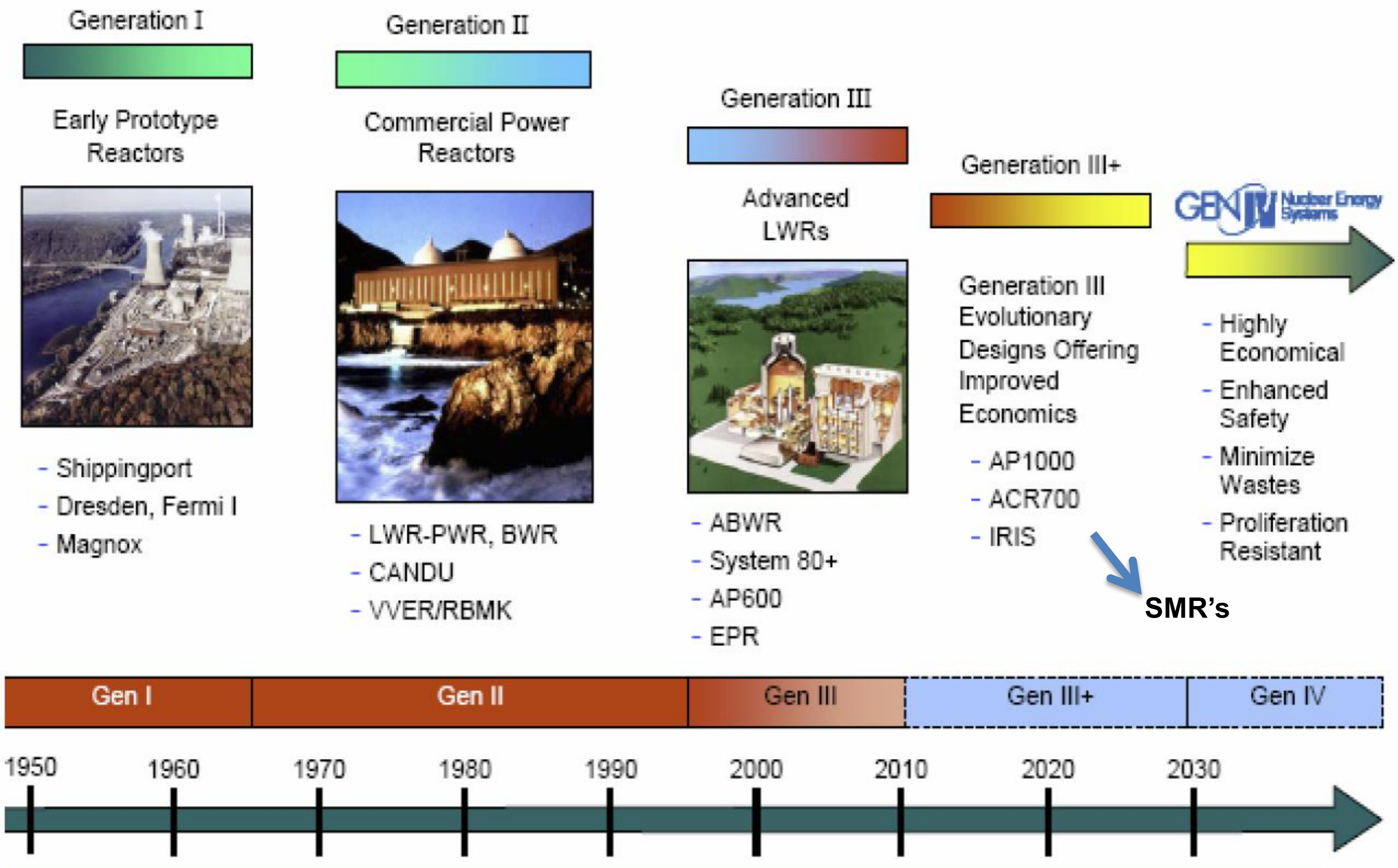
- Global climate change and global warming
- Link to CO_2 emissions
- Pressures to move to non-CO_2 emitting sources of primary energy


Temperature over Antarctica
Atmospheric Carbon Dioxide concentration
Atmospheric Methane concentration
Carbon Dioxide Concentration (ppmv)
325
300
275
250
225
200
175
Methane Concentration (ppbv)
800
700
600
500
400
300
Temperature Relative to Present Climate (°C)
4
0
-4
-8
500
400
300
200
100
0
Thousands of Years Before Present


2050 – 2070 800 ppm
Projected CO_2 Concentrations
2020 – 2040 500 ppm
Measured CO_2 Concentration, 2002 - 370 ppm
Temperature over Antarctica
Atmospheric Carbon Dioxide concentra
Atmospheric Methane concentration
Carbon Dioxide Concentration (ppmv)
800
775
750
725
700
675
650
625
600
575
550
525
500
475
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Methane Concentration (ppbv)
800
700
600
500
400
Thousands of Years Before Present
400
300
200
100
0
Temperature Relative to Present Climate (C)

Emission-Free Sources of Electricity

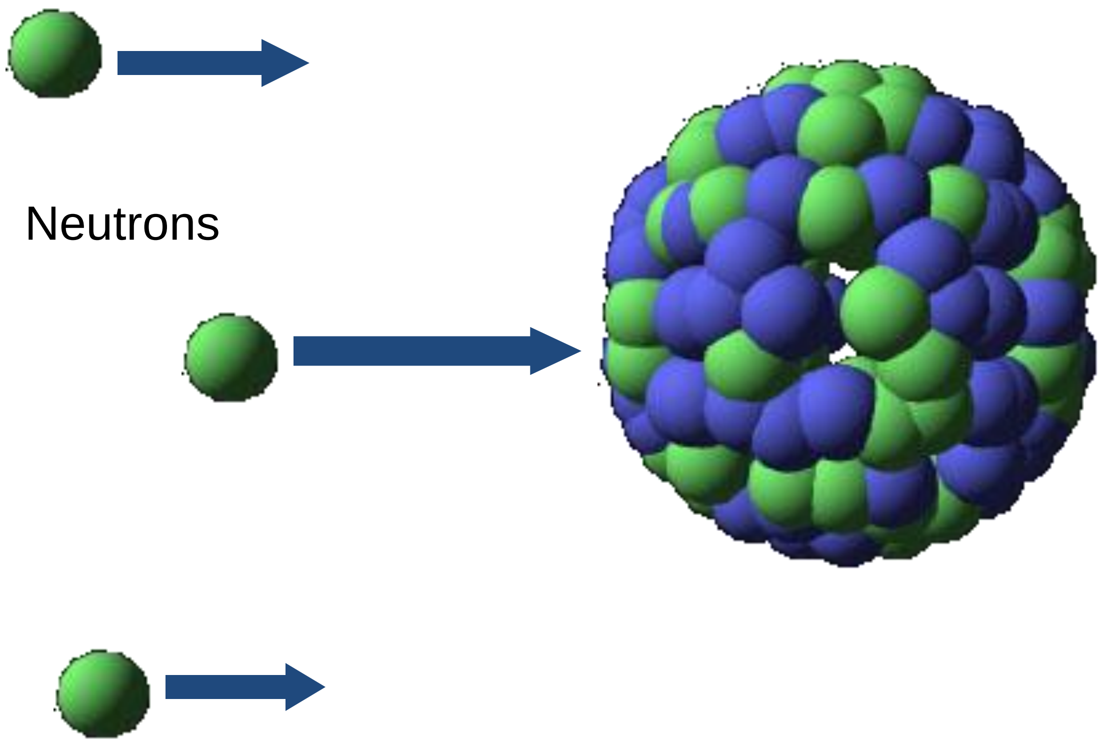



Generation I
Early Prototype Reactors
- Shippingport
- Dresden, Fermi I
- Magnox
Generation II
Commercial Power Reactors
- LWR-PWR, BWR
- CANDU
- VVER/RBMK
Generation III
Advanced LWRs
- ABWR
- System 80+
- AP600
- EPR
Generation III+
Generation III Evolutionary Designs Offering Improved Economics
- AP1000
- ACR700
- IRIS
SMR's
GEN IV Nuclear Energy Systems
- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant
Gen I
Gen II
Gen III
Gen III+
Gen IV
1950
1960
1970
1980
1990
2000
2010
2020
2030

Small Modular Reactors (SMR's)

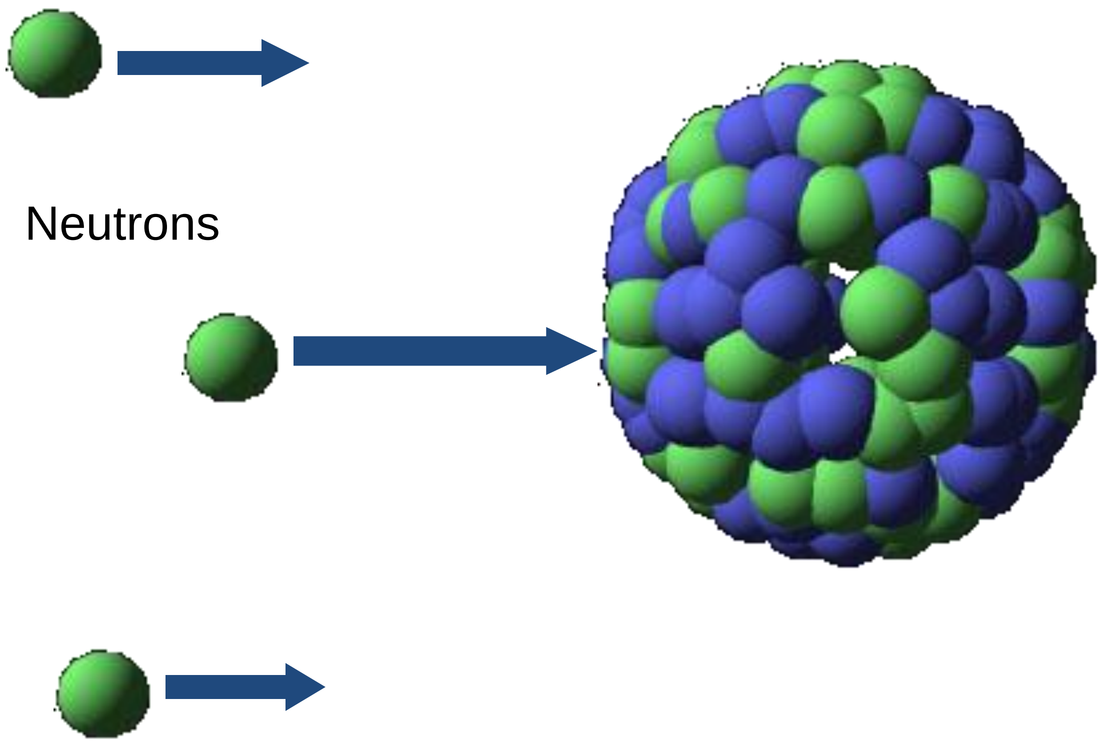
- A more recent development
- An alternative to large scale systems
- Provide opportunities to use nuclear for applications other than electricity
- Power levels
  - 25 Mwe to 300 Mwe

Other Important Parameters



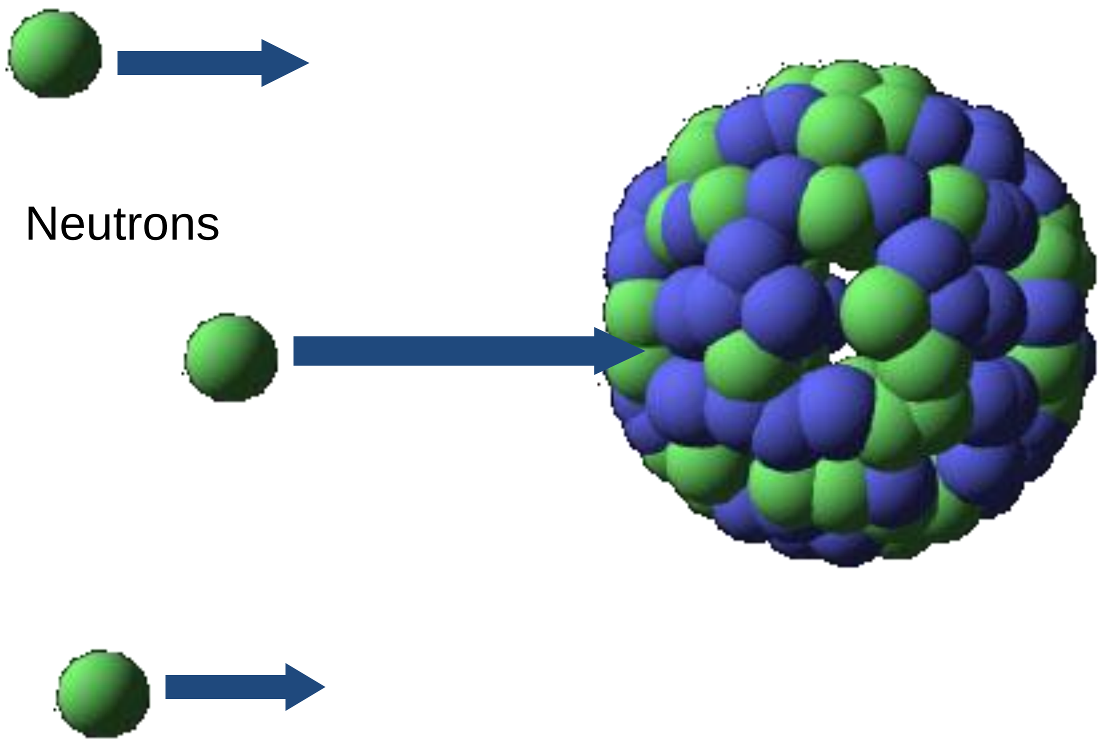
U-238 will absorb a neutron. After two beta decays, becomes Pu-239. Th-232 will become U-233. Both are fissionable.

Other Important Parameters (cont.)



Neutrons absorbed that do not cause fission lead to the heavier isotopes, or actinides. Very long half lives.

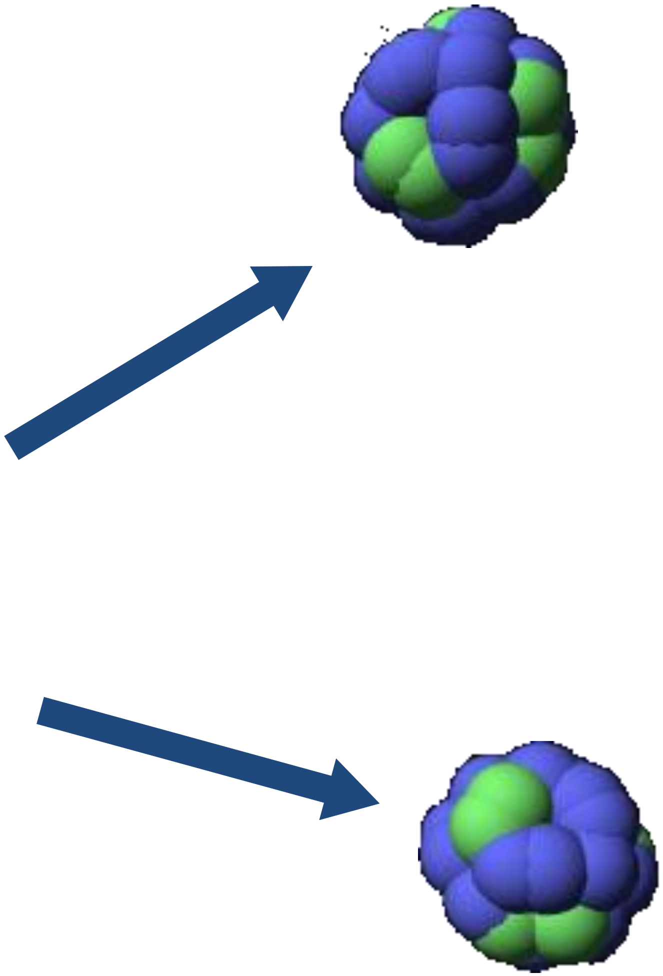
Other Important Parameters (cont.)



Fast, or highly energetic neutrons, cause a higher percentage of fissions when absorbed. Produce more neutrons for each fission.

Nuclear Energy From Fission

Reactor fuel consists of UO_2. After 4 ½ years at the "end-of-life", about 4% of the atoms are radioactive. 95% of these are the fission products, with half lives of about 30 years or less. The remainder are the actinides.



The Story of Dr. Peddicord's Pick-up Truck

Dr. Peddicord's Pick-up Truck

- I have a pick-up truck (that part is true)
- It is a special pick-up truck (that part is true too)

  a 3/4 ton

  Ford F-250

Dr. Peddicord's Truck

- It has two fuel tanks (true)
- The front tank holds 10 gallons (false)
- The back tank holds 20 gallons (false)

Dr. Peddicord's Truck

- I go from College Station to Snook, Texas for lunch (often true)
- Snook has two of the best steak houses in Texas

Dr. Peddicord’s Truck

- I fill the front tank with 10 gallons of gasoline (true)
- I fill the back tank with 20 gallons of water (false)
- I drive to Snook and back for lunch, and use up the 10 gallons of gas (almost true)

Dr. Peddicord's Truck--
What Happens?

- I have gone to Snook for lunch
- However, because it is a special pick-up truck, while using up the 10 gallons of fuel for the trip, I have converted the 20 gallons of water in the back tank to 20 gallons of gasoline

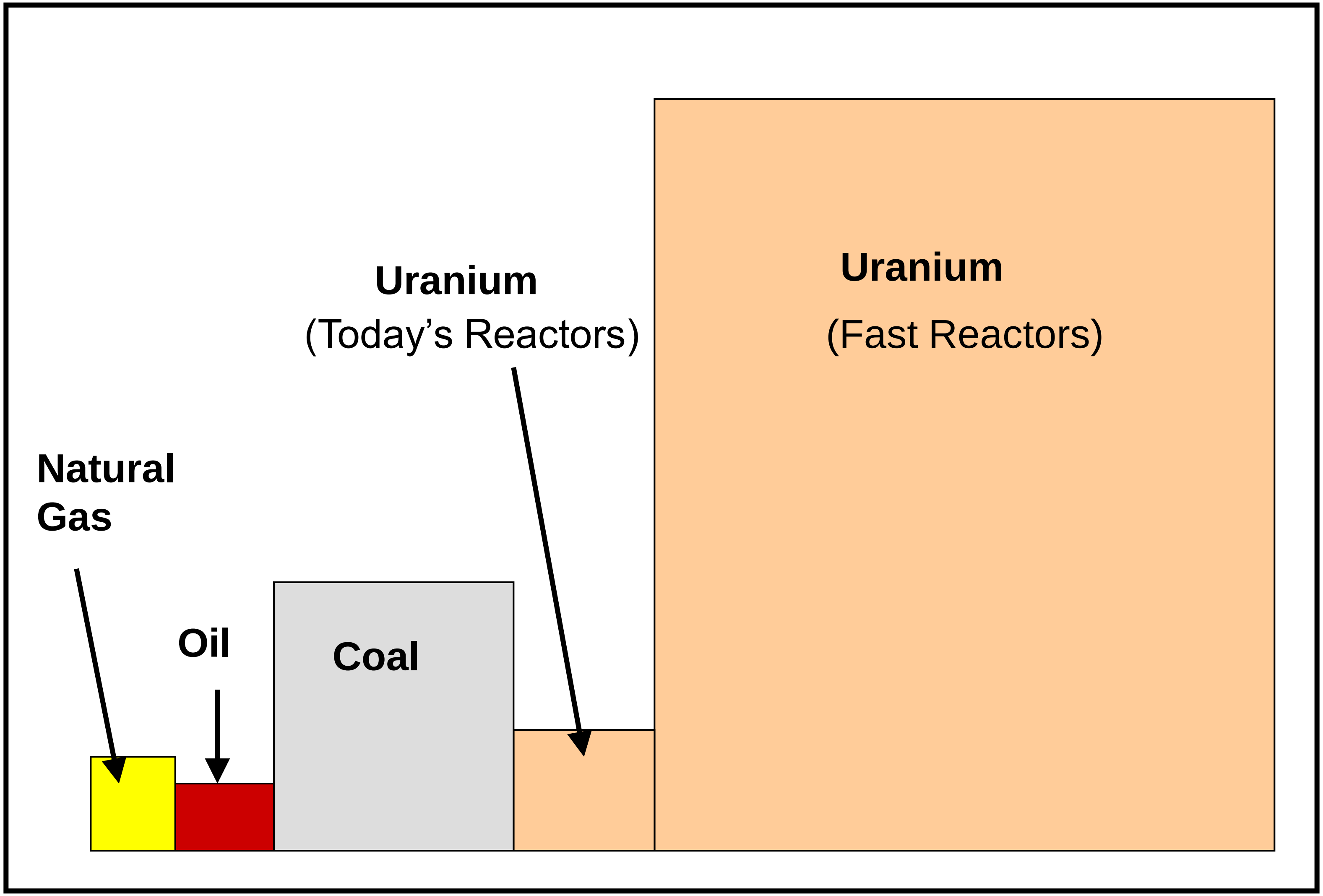
Dr. Peddicord’s Truck

- I have accomplished my primary mission (going to lunch)
- In doing so I have generated twice as much fuel as I have consumed
- I have a ***fast breeder reactor pick-up truck***

Dr. Peddicord's Truck

- Take out the 20 gallons of gas from the rear tank
- Put 10 gallons in the front tank
- Give 10 gallons to Bubba, who also has a special pick-up truck
- Fill our back tanks with 20 gallons of water each
- Go to Snook again the next day for lunch
- Continue to produce twice as much fuel as we use up

RELATIVE WORLD ENERGY RESOURCES

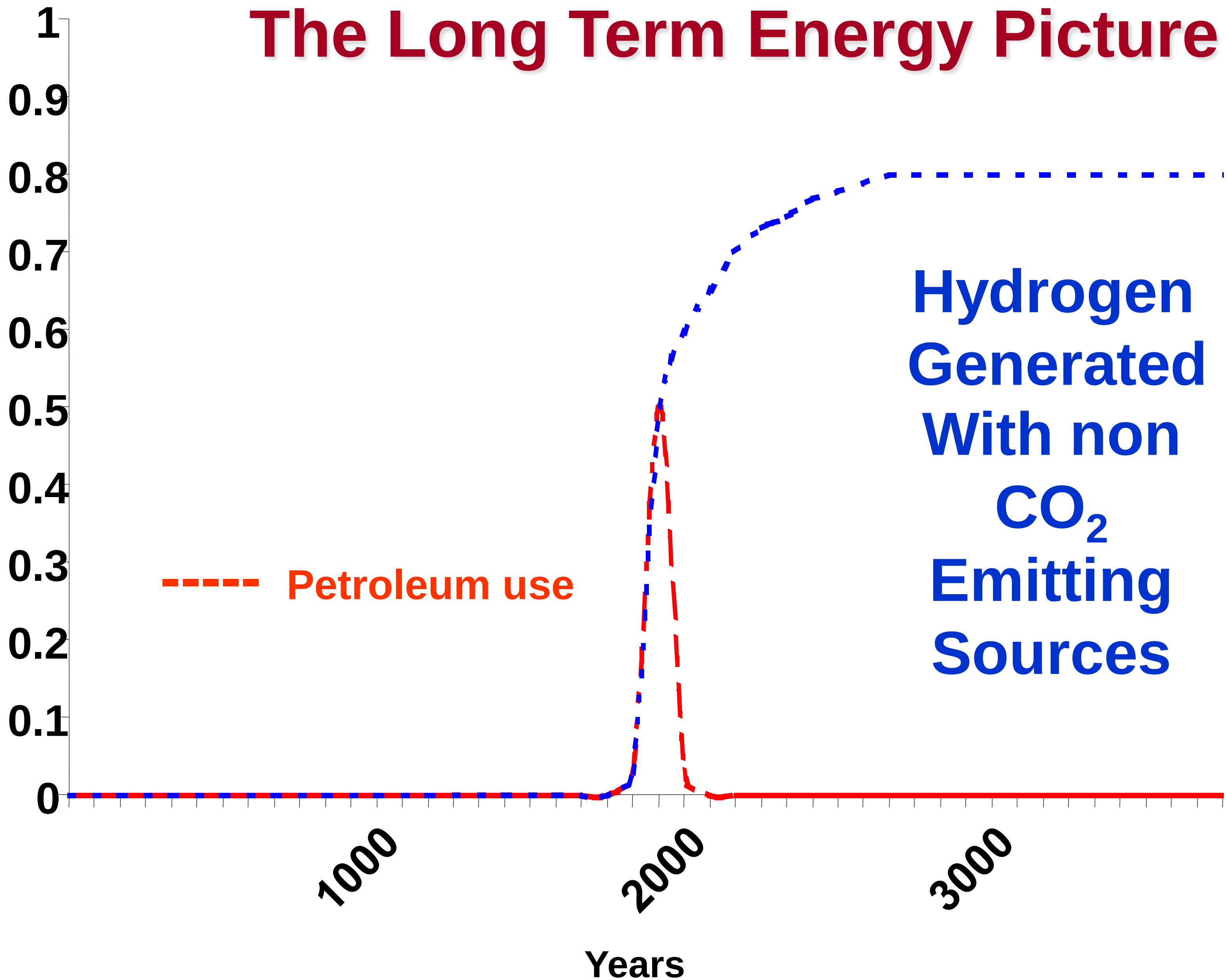


America the Powerless, Alan E. Waltar, Med. Phys. Publ., 1995

And Beyond…

- Nuclear has the potential to meet an expanding set of energy needs
- Breeder reactors can produce more fuel than they consume
- Using advanced reactor designs, nuclear waste can be used to produce energy
- Radioactive fission products may be used for new applications

The Long Term Energy Picture



Conclusions

- The nuclear field is very dynamic
- Real growth occurring around the world
- Improved designs are coming to the market
- New ideas appearing
- Contributes to nuclear energy making increasingly important and expanded contributions to society's energy needs