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

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Uses of Primary Energy

- Electricity
- Transportation
- Heating & Industrial
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

- **China:** 33 units (23 under construction, 14 planned)
- **Russia:** 30 units (11 under construction, 19 planned)
- **India:** 16 units (4 under construction, 12 planned)
- **Japan:** 14 units (2 under construction, 12 planned)
- **South Korea:** 12 units (6 under construction, 6 planned)
- **US:** 9 units (2 under construction, 7 planned)
- **China, Taiwan:** 8 units (2 under construction, 6 planned)
- **Bulgaria:** 4 units (2 under construction, 2 planned)
- **Ukraine:** 4 units (2 under construction, 2 planned)
- **Argentina:** 4 units (2 under construction, 2 planned)
- **Iran:** 3 units (1 under construction, 2 planned)
- **Pakistan:** 3 units (1 under construction, 2 planned)
- **France:** 2 units (1 under construction, 1 planned)
- **Slovakia:** 2 units (1 under construction, 1 planned)
- **Brazil:** 1 unit (1 under construction, planned)
- **Finland:** 1 unit (1 under construction, planned)

**Totals:**
- 61 units under construction*
- 149 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

Uranium-235 nucleus

Neutrons
The Neutrons Can Create a Fission Chain Reaction

\[ {}^1_0n \rightarrow \text{Neutron} \quad \text{Uranium-235} \]
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.
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, \( \sim 2 \text{ Mev} \).
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
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-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

**Current performance:**
- 91.8% capacity factor
- Competitive costs

U.S. NUCLEAR POWER PLANTS
Generation-III and Generation-III+

- Population and economic growth
- Pressure on fossil fuels
- Avoidance of CO\textsubscript{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

- 50% Fewer Valves
- 35% Fewer Safety Grade Pumps
- 80% Less Pipe
- 45% Less Seismic Building Volume
- 85% Less Cable

Westinghouse
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-useable 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)

<table>
<thead>
<tr>
<th>Year</th>
<th>Population (Billions)</th>
<th>GJ/Person</th>
<th>Total Energy (EJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>6</td>
<td>67</td>
<td>400</td>
</tr>
<tr>
<td>2050</td>
<td>10</td>
<td>100*</td>
<td>1000</td>
</tr>
</tbody>
</table>

* NOTE: U.S. Today ~ 300 GJ/Person

100 GJ/Person represents 5 times increase for poor nations
Today  | Straight Scale-Up | INSC | Hold Fossil Levels
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- **Nuclear**
- **Solar**
- **Biomass**
- **Hydro**
- **Fossil**

Energy Consumption (EJ) for the future.

Estimate Year 2050
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
Measured CO₂ Concentration, 2002 - 370 ppm

Projected CO₂ Concentrations

2020 – 2040  500 ppm
2050 – 2070  800 ppm
Emission-Free Sources of Electricity

- Nuclear: 72.4%
- Hydro: 25.3%
- Geothermal: 1.2%
- Wind: 1%
- Solar: 0.1%
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

Hydrogen Generated With non CO₂ Emitting Sources

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Petroleum use

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

1000 2000 3000

Years
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